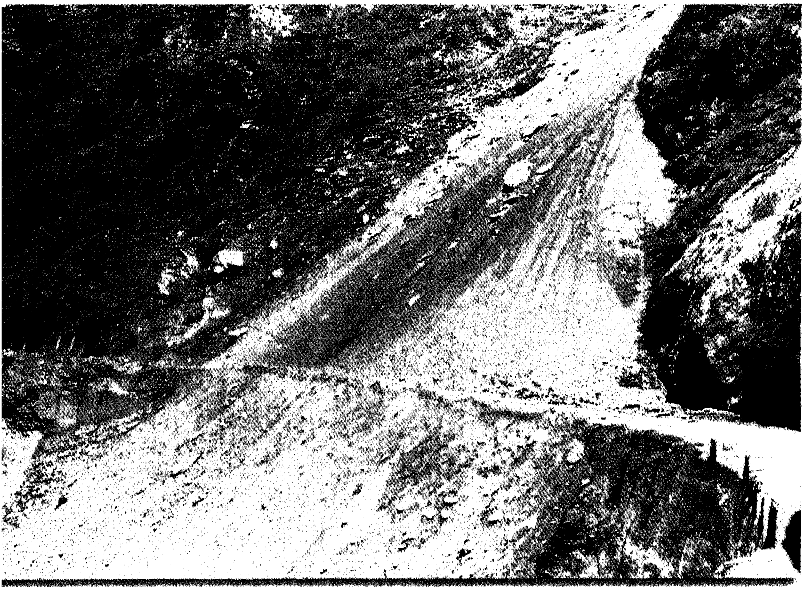
Rains, Landslides and Floods in the Darjeeling Himalaya

Edited by
Leszek Starkel and Subhashranjan Basu



INDIAN NATIONAL SCIENCE ACADEMY
Bahadur Shah Zafar Marg, New Delhi-110002

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INSA EDITOR'S REMARKS

Geologists have always been initiated to explore the physical mechanism that brings changes in the topography of the land, be it the mountainous terrains or the plains. They are interested in finding out the ways and means, which would help prevent further natural disasters from the signatures left by the nature's evil eye through landslides, floods, etc.

"Rains, Landslides and Floods in the Darjeeling Himalaya" has been one of our strong collaborative subjects operating through the ongoing scientific exchange programme between the Indian National Science Academy and the Polish Academy of Sciences. This collaborative project was carried out from 1984 to 1996 through exchange visits of scientists from both the countries and numerous field visits in the Darjeeling Himalaya by the Indian and Polish teams. The former was led by Professor Subhashranjan Basu and the latter by Professor Leszek Starkel. Both the teams worked in close cooperation and brought out tangible results, which are presented in this Volume.

The present monograph titled "Rains, Landslides and Floods in Darjeeling Himalaya" has come out of the voluminous scientific work conducted by both the teams and is not only the product of cooperation between the two Academies but also of the involvement of Institute of Geography and Spatial Organisation, Department of Geomorphology and Hydrology, Polish Academy of Sciences and Department of Geography and Applied Geography, North Bengal University and Department of Geography, Calcutta University through their scientists.

The Indian National Science Academy is thankful to the authors who have contributed to this volume and specially Professor Starkel and Professor Basu whose continuous efforts commencing from the scientific work to the editing of the monograph made it possible to bring out this Publication. I am sure that this volume will be of great interest to the concerned scientific community and will serve as a source of inspiration to young researchers for furtherance of their work. The

Academy is indebted to Professor S K Malik, Editor, *IJPAM* who, in fact, during his tenure as Editor, *PINSA-A*, initiated and promoted the idea of bringing out such a collaborative work in the form of a monograph. I would like to place on record the appreciation of the editorial/production assistance rendered by our Editorial Staff, Shri A K Tagore and Shri M Ranganathan in bringing out this Volume.

01 December 2000

N SATHYAMURTHY
Editor, PINSA-A

PREFACE

Water plays a leading role in the circulation of matter and transfer of energy on the Earth's surface. In the monsoonal tropics rainfall is confined only to 3-5 months and rainy seasons are separated by dry seasons, frequently by deep droughts. In low latitudes, it means great seasonal amplitudes in the river discharge as well as in chemical weathering and bio-mass production.

The rate of runoff, and matter circulation depend on both the slope inclination and channel gradient. The Himalayas, which are the highest and still rising mountain range of the Earth, stand in the zone of monsoonal circulation. It is only to be expected then, that deforestation in such mountains should cause an extremely high acceleration of flood waves and soil erosion, the highest perhaps in all the highland areas of the globe.

The extensive forest clearance in the Darjeeling Hills, which form part of the Sikkim Himalayas, started in the mid-nineteenth century. The continuous rains, at one time reaching 1000 mm in 2-3 days in 1899 and 1950 caused catastrophic landslides and heavy floods described by several geologists and engineers. In 1968, just after the next flood L. Starkel visited this area and published the first detailed description of this event[1] and compared it in the context of extreme events in monsoonal India[2] and all over the globe[3].

This was a starting point for detailed investigations of the team from the Polish Academy of Sciences, which during 1984-1996 explored the problems of causes and effects of heavy rainfalls in this area during the course of 10 expeditional visits. In these visits, participants were L. Starkel (9 times), W. Froehlich (8), R. Soja (3), E. Gil (3), I. Kasza (1), T. Kalicki (1) and J. Syktus (1).

In the mean time, S.R. Basu from the North Bengal University, along with his collaborators S. Sarkar, L. Ghatowar, and S. Lama started detailed examinations of landslides in selected areas of the Darjeeling

Hills as well as of effects of flooding in the alluvial plains. During the visits of the Polish team at North Bengal University in late 1980s an idea was born to put together all this information and to write a Monograph on landslides and floods in the Darjeeling Himalayas. Later it was decided to include also a detailed pattern of rainfall characteristics. The aim of the present book is to demonstrate how such a fluvial system works in the deforested mountains of the monsoonal zone and analyse the frequency and the role of extreme precipitation in causing catastrophic damages over slopes and on the flood plains. These events lead to an examination of the future development of such area where the decrease of natural resources potential is so rapid.

In other parts of the Himalayan range more or less detailed investigations had been organised by English, Swiss, American and Indian scientists, which focus on the problem of accelerated soil erosion and flooding. Many of these were coordinated by ICIMOD (International Centre for Integrated Mountain Development) in Kathmandu, Nepal and personally by J. Ives, who jointly with B. Messerli edited in 1989 a book on "The Himalayan Dilemma Reconciling Development and Conservation". We find that it is urgent to add to this discussion our opinions based on a long time study in one of the key areas of the Himalayan zone and in the monsoonal mountains as a whole.

This book would not have been born without the great help of various people and institutions who not only supplied us with data, but also co-operated in organising the expeditions by offering transport and accommodation facilities.

Grateful acknowledgement especially from the Polish team is due to all officials connected with Darjeeling Planters Association, specially R. Dutta, General Secretary of DPA, who helped so much in arranging visits to the tea gardens and collecting rainfall records. We are also grateful to the Directors, Agents and tea garden Managers of Ambootia, Bannockburn, Ging, Peshok, Pussimbing Tea Estates and several others. Among them we would like to mention S. Bansal from Ambootia Tea Estate, S. Prakash from Darjeeling Plantation Industries and Sharma, the Manager of Bannockburn Tea Estate.

We received similar help from the Forest Division, and especially from S. Patel from Kurseong, who himself carried out detailed investigations on runoff and sediment load joining our team.

Many other persons and institutions helped us in the collection of data like CWC at Jalpaiguri. We are also glad that the Gorkha Hill Council appreciated our activity by organising a talk on landslides (given by L. Starkel) as well as supporting the field-trip of the IGU Commission on Geographic Monitoring and Forecasting in December 1991.

Vice-Chancellor of the University of North Bengal and its Geography and Applied Geography Department rendered fruitful helps for arranging grants for the Indian team, as well as for the hospitality to the Polish visitors which are thankfully acknowledged.

Our Monograph would never have been realised without the Scientific Exchange Programme between the Indian National Science Academy and the Polish Academy of Sciences since 1984 and the personal help of S.K. Sahni, Executive Secretary, INSA and his collaborators, who facilitated the annual or bi-annual visits of the Polish scientists and arranged for S.R. Basu to visit Poland twice and S. Sarkar once.

The Editors of this book express special gratitude to all co-authors and to other colleagues active in this field-work: Izydor Kasza, Tomasz Kalicki, Józef Syktus, S.K. Bhattacharya, Sunil K. Dey, Ms Lipika Ghosh as well as to Ms Maria Klimek for drawing maps and diagrams, Pawel Prokop for assistance in computing rainfall records, Ms Sukla Basu and Ms Srabanti Saha for careful correction of our English manuscript and Ms Ewa Niedzialkowska and Ms Barbara Gnela for help in editorial work.

Leszek Starkel
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Guest Editors
Special Volume on
Rains, Landslides and Floods in the Darjeeling Himalaya

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1

MOUNTAINS OF THE MONSOON TROPICS

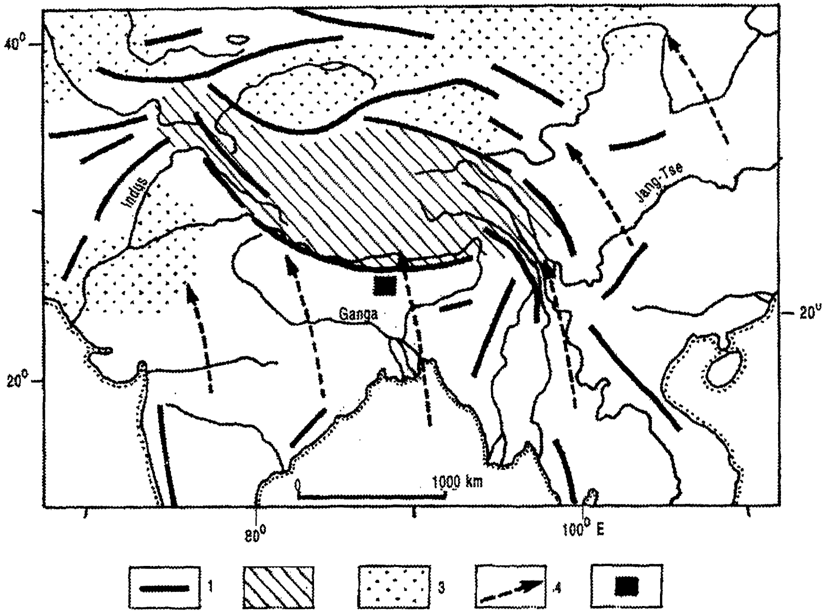
(RAINFALL, HYDROLOGY AND GEOMORPHIC PROCESSES)

The mountains of SE Asia located in the zone of the monsoonal circulation are characterised by several specific features, which all together are responsible for the type and rate of run-off and the geomorphic processes. Among these features are the rainfall regime, intensive upliftment of young mountains and rejuvenated plateaus, areal distribution of rainfall connected with the mountain relief and the important role of extreme events, controlling the acceleration of soil erosion after clearance of natural vegetation.

Precipitation Regime of Monsoonal Tropics

The monsoonal circulation occupies the whole of southern and eastern Asia as well as the central-eastern part of Africa. The specific feature of this zone is the existence of dry and wet season. The word monsoon is either of Arabian origin (word 'mausim' means water vapour) or Malayan one 'monsin'[4]. The length of dry and wet seasons as well as the annual totals of precipitation vary with the distance from the source area, with relief and also from year to year. In case of India the activity of summer rainy monsoon is controlled by cyclonic tracks going from the Bay of Bengal, by altitudinal location of the monsoonal troughs, position of mid-tropospheric low-pressure system, off-shore and onset vortices and by low level equatorial jet-streams[5,6]. Especially important are the breaks of monsoonal circulation in spring and in autumn (September-October), when the SW monsoonal trough may reach the Himalayan front and heavy continuous rainfalls are pouring down[7]. The air masses slide to the west along the Himalayan barrier and may enter more or less deeply into the semiarid zone[2] (Fig. 1.1). The precipitation totals fluctuate from year to year even in most humid part like the Meghalaya, where the total annual precipitation fluctuates from below 10000 mm to 25000 mm[8,9].

In various parts of India every year witness either floods or droughts[10-14]. The maximum observed daily rainfall fluctuates all over India from 70 mm in Rajasthan to 900 mm in Meghalaya[15]. But the



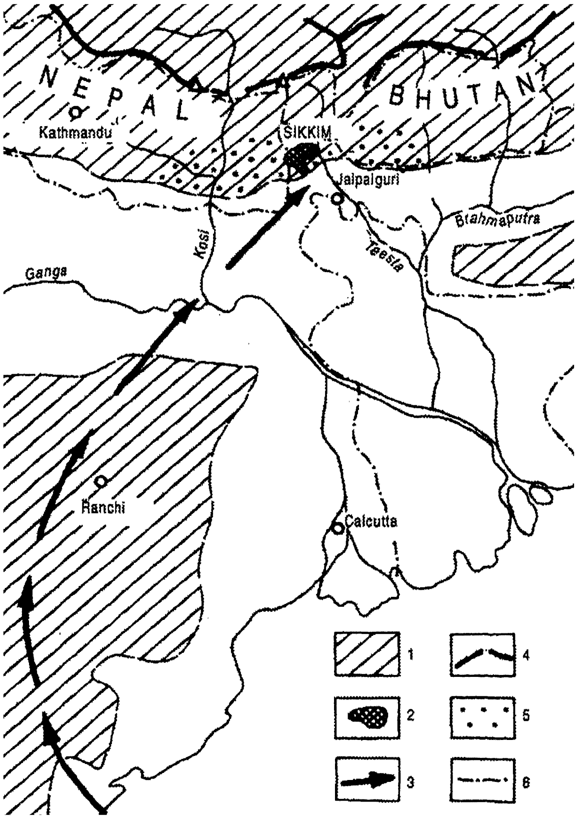
1. High mountain barriers, 2. Tibetan plateau, 3. Desert areas,
4. Main directions of summer monsoonal circulation, 5. Area of investigations

Fig. 1.1: Darjeeling Himalaya in the monsoon Asia

areal distribution of rain during extreme events is very diverse, even the rainfalls (over 100 mm) occupying upto 30-40 thousands km^2 have a very small central area of several dozens or hundreds of km^2 in size, where the precipitation totals may exceed 500-900 mm in 1-3 days[16]. The character of monsoonal rains especially in the deforested mountains is reflected in the run-off ratio, which in the Nepal Himalaya fluctuates between 40% and 90%[17].

Young Mountains

The monsoonal part of Asia belongs to the most active parts of the Alpine orogenic belt or to the reactivated old block (Fig. 1.2). In both cases rate of uplift is rather high. The uplifted blocks like the large Deccan Plateau or the small Meghalaya Plateau are deeply dissected only on their margins. On the contrary the whole Tibetan block with the marginal Himalayan range to the south, 6-8 km high, still reflects differential intensive uplift. The rate fluctuates from 0.5 to 5.0 mm per year[18-20]. The higher central part of the Himalaya overthrusted earlier along the Main Central Thrust. The younger Main Boundary Thrust separates the



1. Mountains and uplands, 2. Area of investigations, 3. Cyclonic track of October 1968, 4. Main Himalayan range, 5. Area damaged by heavy rainfall 2-5 October 1968, 6. State boundaries

Fig. 1.2: Position of Darjeeling Himalaya and extreme rainfall in October 1968 (after Starkel[1])

lower Himalaya from the Siwaliks built of the Neogene-Quaternary deposits filling the foredeep. These Siwaliks form several active schuppen structures, separated by the Himalayan Frontal Tectonic Line from the plains with horizontally bedded sediments. Their thickness reaches in Bengal 4-14 km depth[21]. Himalayan mountain range is dissected on their southern slope by many transversal river valleys. The depth of their incision depends on the uplift rate, rock resistance and the power of flowing water. Only the greatest rivers like the Brahmaputra, the Kosi or the Tista may follow the uplift rate[22,23]. On the less resistant rocks, the uplift may be compensated by total denudation[24,25]. In the case of the Himalayas the present-day denudation rate (accelerated after the forest clearance) fluctuate between 0.7-1.5 mm yr^{-1} in the Eastern Himalaya[26] and rise to 4.7 mm in the hilly Tamur basin in Nepal[27]. In case of the High Himalaya the uplift rate is calculated to be 20-70 times higher than the denudation rate[20]. This is partly connected with the vertical zonality of climate and character of geomorphic processes in the high mountains. In case of the Himalaya, the tree line, the snow line and the permafrost limit are exceeded. Therefore the higher belts are not more under control of the environment of humid tropics, but are still influenced by the monsoonal circulation, responsible for distribution of precipitation.

Mountains as the Climatic Barriers

The high mountain ranges and escarpments block a free monsoonal circulation and therefore the Tibetan Plateau is invaded very rarely by humid air masses. But this effect is clearly expressed in the spatial rainfall pattern. The wind-exposed site gets much higher precipitation than the opposite lee side[28]. In case of India at the margins of the Western Ghats, Meghalaya Plateau and the Himalayan front this contrast is very high and also the inversion of rainfalls is noted[2]. The region of Pune over the Deccan Plateau receives rainfall below 500 mm, when Mahabaleshwar on the western edge gets about 6000 mm. In case of Meghalaya located just north of the Bay of Bengal the drop in annual rainfall is even more spectacular (from 12000 to 2000 mm). In the eastern Nepal as well as in the Darjeeling Hills (see below) the southern slopes of external hills get above 2000 mm of annual rainfall, whereas the shadowed lower inter-montane depressions get even below 1000 mm and again the annual total rises to 2000 mm on the slopes of the High Himalaya[29,30]. Exposure to rain and inversion of rainfall are the two important elements, which have been avoided in various calculations of run-off, soil erosion and bio-mass potential.

Extreme Events and Anthropogenic Pressure

In the relief evolution of mountain areas the extreme events play the leading role. This fact has been stated in different climatic zones starting from humid tropics and mediterranean zone upto to temperate, arid and semi-arid and even in the polar one[3,31-37]. In the tropical climate with monsoonal circulation among these extreme rainfalls, there are heavy downpours, mainly localised, with intensities of 1-3 mm min^{-1} causing mass movements and local floods[2,3,38,39] as well as continuous rains lasting for 2-4 days covering upto 50000 km^2 or more and causing large floods[26]. With such continuous rains are frequently associated high intensity downpours and therefore the rainfall totals may reach 1000-2000 mm[39A]. During such events in the deforested highland area the denudation exceeds several hundred millimeters and the transformation of slope and channel systems proceeds simultaneously. An event of a similar nature occurred in October 1968 in the Darjeeling Himalaya[1]. As it was observed in several deforested basins the rate of soil erosion there is 1-2 orders higher than in the forested areas[33]. The observations on the frequency of 1-3 days long heavy rainfalls indicate that usually in one century we may expect in every region of India several rains of high intensity and duration[10], as well as several floods[40]. The deserted landscape in the region of Cherrapunji with totally eroded soils[2,41] is the spectacular example of human intervention in the monsoon climate.

Location of Sikkim Himalaya and Darjeeling Hills

The region, under study is located just north of the Bay of Bengal and the extensive Ganga delta abutting the subsiding Himalayan foredeep. This is a wide Bengal Gate between the Deccan Plateau in the West and the narrow horst of the Meghalaya Plateau in the East (Fig. 1.2). The cyclonic tracks passing from SW and S may easily reach the Himalayan border. Just here are recorded the highest annual rainfalls in the whole Himalayan belt, fluctuating at the Mission Hill (east to Tista river) between 5000 and 8000 mm. In the foredeep are growing here two large alluvial fans of the Kosi and the Tista rivers[42,43] and several others with braided channels and frequent avulsions (Fig. 3.9). The Darjeeling Hills, an area under study, are just drained by the Tista, the Mahananda, and the Balasan rivers with their numerous tributaries.

2

HISTORY OF RESEARCH AND METHODS

The Darjeeling Himalaya is a fragile terrestrial system, which is much too often disturbed by various environmental catastrophies. As such, the region has encouraged intensive study and investigation by various research groups, government authorities, renowned geologists, geographers and engineers. The physical condition, the climatic characteristics, the condition of the forest cover, the causes and consequences of slope failures etc., have all been studied sometimes in great detail.

One of the first attempts of study in the Darjeeling Himalayas was made by JD Hooker (1854)[43A]. During his two years long (1848-1849) travels he traced the regional domal picture of gneisses and observed the overlying sedimentary bedding. He recorded the occurrences of "gravel beds" in between the river channels, extending southwards for about 32 km from the base of the mountains. According to him these formations originating from glacial or glacio-fluviatile processes are cut into flat topped terraces, flanking the spurs of the mountains. He studied such stratified sand and gravel terraces, flanking the Balasan river. He also talked about the character of weather in the Tista and Great Rangit valleys and made a fairly detailed study of the vegetation of the Darjeeling Hills. Moreover Hooker gave a systematic report for the first time on the landslides. Prior to 1899, landslide events were almost unrecorded. During 1848-1849 travels he came across several enormous landslips and wrote that the most prominent effect of the steepness of the valleys is the prevalence of landslips which sometimes descend for 1000 m, carrying devastation along their courses and are increased in violence and effect by the heavy timber trees which sway forwards, loosen the earth at their roots and give impetus to the mass.

Geological investigations in Darjeeling and the adjoining regions were continued in 1874 by F.R. Mallet[73]. He was the first to classify the metamorphic rocks into the Daling Series and Darjeeling Gneiss. Following P.N. Bose (1900)[43B], who investigated the mineral resources

E.J. Garwood (1903)[43C] produced the first general map. E. Suess (1885-1909)[43D] discussed the Darjeeling gneisses and regarded nappism as a solution for many Himalayan puzzels. A Heim and A Gansser (1939)[21] visited the Tista Valley. New mapping by the Geological Survey of India started since 1950. S.K. Ray (1947)[43E] has carried out valuable work on the metamorphism of the rocks of Darjeeling area and A.M.N. Ghosh (1950)[43F] detailed geological mapping in parts of the Darjeeling Himalayas. Lately, JB Auden (1956)[43G] and others of the GSI have examined the Tista gorge.

Landslide is perhaps the most hazardous among all the environmental catastrophies threatening the Darjeeling Himalaya. It is also the most widely investigated phenomena. Apart from the valuable records of Sir Joseph Hooker, the Government of West Bengal appointed a committee under TH Holland to enquire into the causes of slips and to suggest preventive measures after landslips of September 1899. According to him, the slips confined to the soil cap overlying the gneisses, and the immediate cause of the catastrophy was excessive aggraved by the cutting of slopes for artificial needs[44].

H.H. Hayden (1912) visited Darjeeling in October 1911 to advise the Bengal Government with regard to the protective measures necessary in the Happy Valley Tea Garden. L. Fermor carried out detailed geological survey in the Happy Valley in 1912. His work was continued by R.C. Burton in 1914. The map prepared by him showed physical conditions of rocks, and included suggestions for protective measures[45].

A.M.N. Ghosh visited Darjeeling as a representative of the Relief Committee after the landslides of June 1950. According to him half decomposed, unconsolidated regolith resting on steep slope, were mobilised due to heavy rainfall. He recommended the construction of revetment walls with holes for the construction of heavy structures[43F].

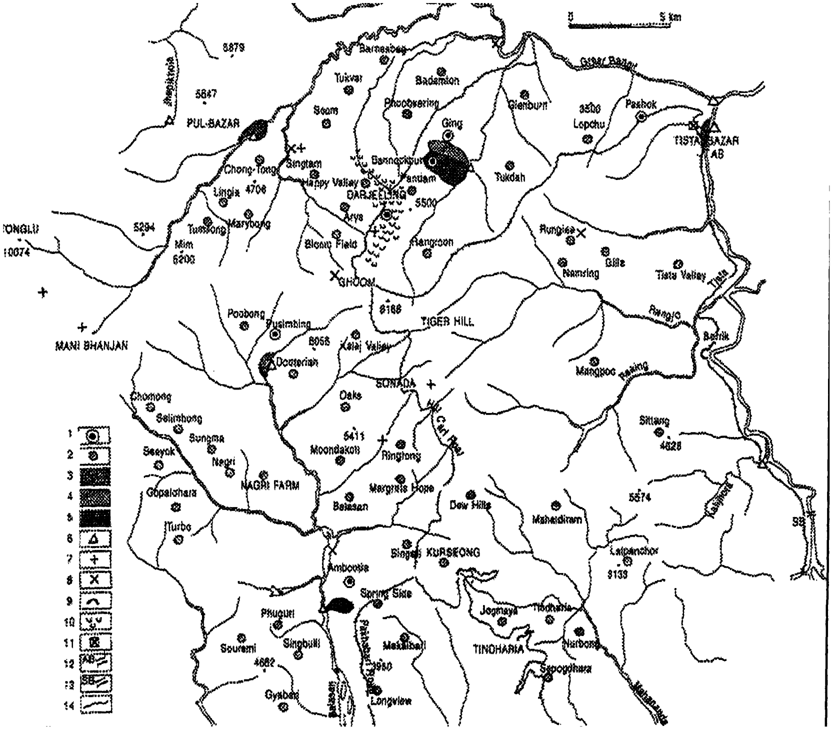
In 1951, S.P. Nautiyal and K.K. Dutta were sent to Darjeeling to study landslips on behalf of the Geological Survey. S.P. Nautiyal[46,47] carried out detailed examination of the hill slopes of Jalapahar and Lebong cantonment area. K.K. Dutta[48] observed that except the ridge tops no portion of the town is absolutely stable. His recommendations were as follows: 1. Reduction of the angle of slope, 2. Prevention of percolation and seepage, 3. Provision of drainage and 4. Retaining walls. He also observed that the eastern slope of Darjeeling ridge was steeper and slips are more frequent and destructive here than on the western slope.

In 1955, extensive investigation was carried out by G.N. Dutt[49] in the Lish and Chel basins in the Kalimpong subdivision, subsequent to the 1954 flood. The objective was to find out the causes of the recent floods to suggest remedies for the control of flood and for soil and water conservation. A detailed geo-technical study of the Lish and Gish valleys was made in connection with the work of the State Flood Control Board, Government of West Bengal, during 1957 under M.S. Jain[50]. The relationship between the structural and lithological characters of the rocks found in the catchment areas and the landslides were traced by statistical analysis of these slides. The part played by quarrying operations of coal seams and the consequent soil erosion of hill slopes is discussed.

Quite a number of north-south trending fissures developed on the eastern slopes of Lebong Cantonment as a result of huge landslides, which took place in Lebong, after heavy rain early on the 25th September 1952. These were examined by P.C. Hazra.[51]

In 1965-66, S. Ray and S.B. Sen Sarma[105] carried out detailed study of the slope pattern around Darjeeling, thereby assigning each segment of slope its respective status in the accepted nomenclature of waxing, waning and critical slope inclination. The role of such inclination in causing and guiding slides had been discussed and an attempt had been made to assign the degree of stability of the slope for engineering construction. For this purpose the authors prepared a detailed isotan map of the Darjeeling ridge.

In 1968, L. Starkel[1,52] made extensive study in the Darjeeling hills to investigate the role of catastrophic rainfall of early October in the shaping of the relief. The author stayed in the region from 17th December 1968 to 3rd January 1969, when the slope damages were fresh, as after 5th October 1968, no heavy rainfall occurred. The observations assembled the dates, the amount and intensity of the rainfall, and the morphological consequences. The author also tried to map these forms in the tea estates of Bannockburn, Chongtong, Poobong and Ringtong as well as in some forest blocks and Tista valley near Tista Bazar (Fig. 2.1). The detail rainfall characteristics were later also published in the Indian Journal of Meteorology and Geophysics (1969).



1. Rain gauges for which long series of daily records were collected, 2. Rain gauges for which annual and some extreme rainfalls data were collected, 3. Areas mapped in 1968, later resurveyed, 4. Areas mapped in 1980-th later resurveyed, 5. Ambootia landslide, 6. Channel cross-sections resurveyed one or several times, 7. Places visited in 1968, 8. Places visited in 1984 or later, 9. Landslides along roads surveyed by S.R. Basu and S. Sarkar, 10. Landslides in Darjeeling town (compiled by S. Lama), 11. Experimental basin of Pashok Jhora, 12. Anderson bridge, 13. Sevoke bridge, 14. Hill Cart Road and other main roads

Fig. 2.1: Map of investigated areas and rainfall stations

B. Biswas and G.V. Bhadram[53] later on made a similar study on 1968 events. Some characteristic of 1968 flood was presented in the monograph of A. Agarwal and S. Narain[54]. Landslides formed in October 1968 were also surveyed and elaborated by several geologists. Among them, the Tista river landslides were studied by B.N. Sinha *et al.*[55] A team from the Geological Survey in Calcutta prepared a map of landslide valley in Ambootia, but it had been never published.

In 1972, Japanese geomorphologist T. Nakata published his thesis on the geomorphic evolution of the mountain front of the Darjeeling Himalaya and crustal movements based on detail survey of terraces and alluvial fans between Balasan and Chel rivers[71].

S.R. Basu and S. Sarkar[56,57] carried out detailed case studies of the causes and consequences of landslides at the 27 km Bustee and Tindharia along the Hill Cart Road and Pankhabari Road. The methodology comprised of the quantitative determination of the instability factor of slope, analysis of soils, detailed tabling of the composition and orientation of geological structures and the examination of geomorphological process together with the study of the nature and extent of human interference.

The problem of quarry-operations and their effects on the environment was taken up by S.R. Basu and L. Ghatowar[58-63]. For this particular theme, the Lish-Gish Basin was taken up as a case study. It was revealed that the unscientific modes of quarry-operations in the coal mine of Chunkola, have not only upset the critical conditions of stability of hill-slopes but have also provided the tributary with enormous loads which, in turn had incapacitated the parent rivers, the Lish and Gish. Thus causing them to overflow the banks in the plains. Comparable situations were sighted in cases of defunct coal-quarries in Ramthi and Lethi valleys.

In 1984, a Polish team from the Department of Geomorphology and Hydrology in Cracow, Institute of Geography, Polish Academy of Sciences, led by L. Starkel started detailed investigations on the role of extreme and normal rains in the evolution of slopes and river channels. During their 10 visits (each of a duration upto one month) they not only collected old records, but also surveyed repeatedly various forms and registered various processes during these years (February 1984, November 1986, September 1987, July 1988, November 1989, February 1991, December 1991, January 1993, November 1994, January 1996).

With help of the Darjeeling Planters Association and various Tea Garden Managers, L. Starkel and his team collected the daily and monthly rainfall records especially for stations in Darjeeling, Bannockburn TE, Peshok TE and Ambootia TE as well as annual and extreme rainfall records for great number of stations (Fig. 2.1). All these data helped to calculate the general trends of annual precipitation, frequency of extremes, as well as to elaborate maps of areal rainfall distribution with isohyets.

Various slope forms were surveyed and mapped, especially the largest active landslide valley of Ambootia[64,65]. On the slopes, measurements of soil parameters, infiltration rate, overland flow, water conductivity of springs and others were also carefully made. During several heavy rains (in 1987, 1990) or just after them observations were made of processes in statu nascendi to supplement earlier observations.

In the river channels of various orders detailed investigations on cross-sections and longitudinal profiles (in case of Rangnu creek and Posam creek) were repeated[66]. In case of small Peshok Jhora, S. Patel from Forest Division carried out studies on discharge and sediment load.

In 1989 S. Sarkar under the leadership of S. Basu elaborated a monograph on the environmental changes in the Mahananda basin presenting the daily data on river discharges and suspended load[67-69]. Later in 1994, S. Lama in her dissertation[87] presented a detail picture of landslides in the Darjeeling town under the joint guidance of S.R. Basu and S. Sarkar.

3

ENVIRONMENT

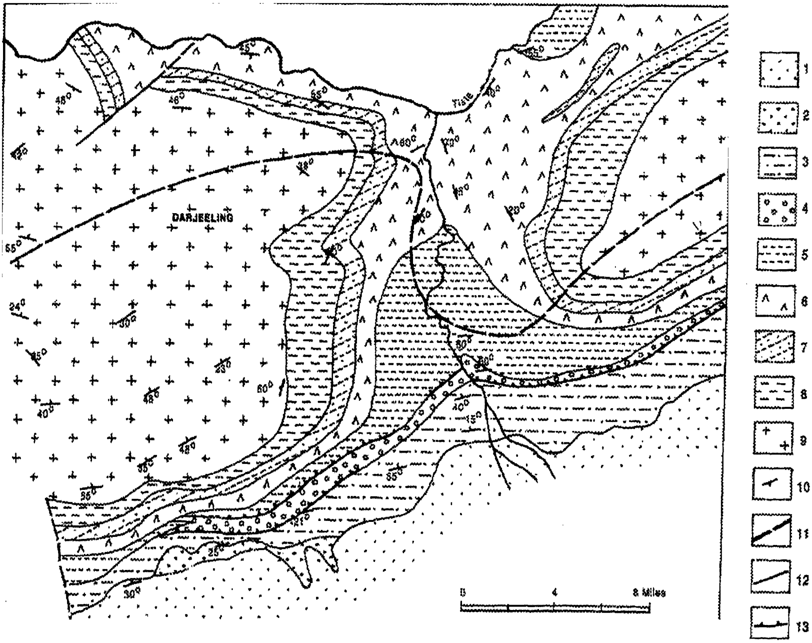
3.1 Geology

Introduction

The Darjeeling Himalaya is separated from the foredeep of the Ganga-Brahmaputra Plains by two active tectonic lines (Main Boundary Fault and Himalaya Front Tectonic Line) in the zone of the subduction of the Indian block (Fig. 3.1). It is built of a sequence of overthrusts pushed southwards and dipping to the north (Fig. 3.2). Going from the north there are the medium resistant Darjeeling gneisses, the Daling metamorphic rocks of varying resistance from phyllites to quarzites and the Damuda shales and sandstones interbedded with coal seams.

The rocks of the Daling and Darjeeling Gneiss have also been thrust over the Damuda[70]. The Daling Series and the Darjeeling Gneiss group represent a major synformal structure and the formations in the northern part and southern part, form respectively the northern and southern limbs of the synform. The trace of the axial plane of this major synform trends about ENE-WSW. This major synform appears to have been further refolded as evidenced by the formation of the northerly plunging cross-fold which controls the flow of the Tista river in this area.

This synform probably forms a part of the major recumbent fold, which has been postulated by the earlier workers to explain the structure of the Darjeeling Himalaya[21]. The Damudas are separated by the Main Boundary Fault (MBF) from the narrow thrust of Siwaliks built of Tertiary molassic deposits. The Siwaliks are separated by the active Himalaya Front Tectonic Line (HFTL) from the subsiding Bengal Basin (Fig. 3.3). Some fresh tectonic scarps and exposures with the Tertiary overthrust over the alluvial deposits indicate, that the movement continues. The uplift in the Eastern Himalaya is calculated to be of the order of 0.5-4 mm per year[71] the generalised sequence of the various geological formations of this area is presented at Table I and Fig. 3.1.



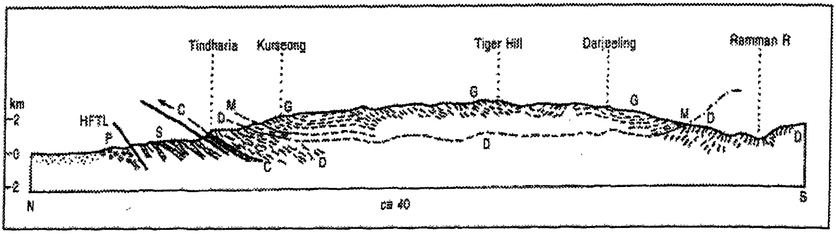
1. Alluvia, 2. Older Pleistocene alluvia, 3. Siwaliks, 4. Damuda series, 5-6. Daling series (5. Slates, 6. Chlorite quartz schists), 7-9. Darjeeling gneiss (7. Mica schists, 8. Garnetiferous mica schists, 9. Coarse grained gneisses), 10. Strikes and dips of beds, 11. axis of major synform, 12. Fault, 13. Thrust contact

Fig. 3.1: Geological map of Darjeeling Hills (after Pawde and Saha[70], Mallet[73], Gansser[18] and others)

Table I: Geological succession of Darjeeling Himalaya

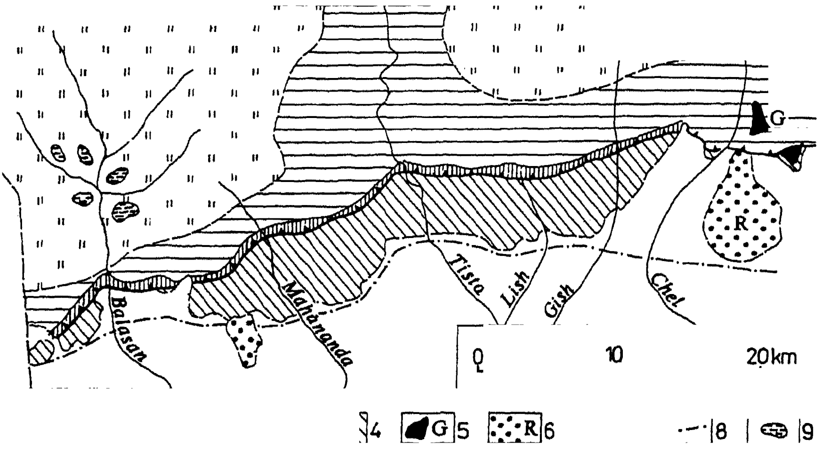
Age	Series	Lithological characters
Recent (Holocene)	Sub-aerial formations (soil, alluvia, colluvia)	Younger flood-plain deposits of the rivers composed of sand, gravel, pebble, etc. and soil covering the rocks
Pleistocene	Raised Terraces	Sandy, clay, gravel, pebble, boulders etc. representing older fluvial deposits
	Himalaya Front Tectonic Line (HFTL)	
Pliocene to Lower Pleistocene	Siwalik	Micaceous sandstones with slaty bands, seams of graphitic coal, silts and minor bands of limestone
	Main Boundary Fault (MBF)	
Permian	Damuda Series (Lower Gondwana)	Quartzitic sandstones with slaty bands, carbonaceous shales, seams of graphitic coal, lampro-phyre sills and minor bands of limestone
	Thrust fault of nappe outlier	
Precambrian	Daling Series Darjeeling Gneiss	Slates, chlorite-sericite schists Mica schists, coarse grained gneiss

Based on: Mallet[73], Gansser[18] and Pawde and Saha[70]



A–Alluvium, P–Pleistocene boulders, S–Siwaliks, C–Damuda series, D–Daling phyllites and slates, M–Mica schists, G–Darjeeling gneisses, MBF–Main Boundary Fault, HFTL -Himalayan Front Tectonic Line

Fig. 3.2: Geological schematic section across Darjeeling Hills (after Heim and Gansser[21])



1. Darjeeling gneisses, 2. Daling series, 3. Damuda series, 4. Siwaliks, 5. Gor-bathan surface, 6. Rangamati surface, 7. Main Boundary Fault, 8. Himalaya Front Tectonic Line, 9. 200-300 m high erosional surface along Balasan valley

Fig. 3.3: Geology and Quaternary levels in the marginal part of the Sikkim Himalaya (based on Pawde and Saha[70], Nakata[71] and own observations)

A brief description of the various formations of the Darjeeling Himalaya is given below:

a) *Raised Terraces*

The recent to sub-recent formations usually form a fringe along the hills, though at places, their presence are noticed within the hills. These comprise of gravels, pebbles and boulders mixed with ferruginous sand or clay. The formation is somewhat consolidated, stratified and shows evidences of upheaval at places[18]. The reddish colour of the formation is due to oxidation and thereby proves its antiquity as compared to the alluvium of recent age noticed in the area further south. High level terraces comprise of a part of the southern plains known as the Terai[43,71]. In the Tista valley at Kalijhora the 40 m high terrace after TL dating represent the upper Pleistocene[72].

b) *Siwalik*

The Siwalik system comprising of soft sandstones, mudstones, shales and conglomerates along with their bands of marly shales and lignite are found to constitute the foothills of the outer Himalaya. Altogether, the Siwaliks have been reported to be missing over certain stretches good exposures of the Siwaliks occur along the Tista river the Hill Cart Road and Pankhabari Road as well as in the Lish river section. The sandstones are usually thick (3000 m), often very massively bedded[73]. The general strike of these rock formations is NNE-SSW to NW-SE, with dips varying between 30° to 60° N.

c) *Damuda Series*

Abutting against the Siwaliks are found coarse-grained hard sandstone, quarzites, carbonaceous shales and slates. They are equivalent to the Gondwanas of the Peninsular India. The maximum width of the Damuda's is about 2.5 km along the Tista valley and it thins both to the east and west. The total thickness of the rock formation reach 1000 m. The beds have a generalised strike of ENE-WSW with dips varying between 40° and 90° in north-westerly direction. The best coal seems measure about 3 m in thickness near Tindharia.

d) *Daling Series*

The Daling series comprising of sericite and chloritic slates, phyllites and schists associated with quartzite rest over the Damuda[73]. They are well developed all along the course of the Tista River and form the core of the domal uplift running north-south for more than 50 km. The Daling rocks are also well developed in between Tindharia and upper-Paglajhora along the Hill Cart Road. The rocks are traversed by quartz and quartzo-felspathic veins. The rocks are often highly metamorphosed and jointed. The most impressive geological feature is the progressively increasing metamorphism of the Dalings upwards. Slates form the lowest bed. The transition from slates to chlorite-sericite schists is gradual[70].

e) *Darjeeling Gneisses*

In the higher reaches of the hills, the Dalings gradually grade into more metamorphosed rocks known as the Darjeeling Gneisses. Along the eastern and western borders, the gneisses begin at approximately 1000 m above sea level (Fig. 3.1).

The dips are irregular but varies from 40° and 65°, northerly near Kurseong and southerly near Darjeeling. The Darjeeling Gneisses are highly foliated and the foliation dips being generally from north to north-west, the amount of dip ranges from 30° to 50°; within the confines of Darjeeling town the foliation dips of the rocks are generally towards the east, ranging from 20° to 40°. There are two prominent sets of joints in the gneiss, one running roughly NW-SE and the other NNW-SSE. Both the joints have steep westerly dip varying from 40° to 70°. The general direction of the hill spurs agreeing with the joint directions, indicate that blocks of rocks loosen easily along joints.

3.2 Soils

The weathering of lateritic type is the substantial mechanism in the transformation of substratum. The variable thickness of regolith and soils in the longitudinal slope profiles depends on the rate of weathering and intensity of mass movements connected with slope gradients. In many cases the thickest soil profiles are composed of regolith *in situ* and superimposed colluvial or proluvial deposits. These alternate with sections of very thin soil cover or even with exposed bedrocks. Most frequently the regolith several meters thick is preserved over flattened watersheds or spurs in the upper valley reaches. At their base the weathered gneisses form the rounded less decomposed structures of core stones.

The basic soil types are yellow and red-brown soils and brown forest soils, all of siliceous and aluminous type. Red and yellow soils have developed on gneisses and schists along the upper part of slopes.

Over the Siwaliks are developed coarse pale yellow to red brown soils, on the Daling shales clayely dark grey soils and on the Gondwanas mainly sandy soils. Over the Darjeeling gneisses prevail red to brown silty and sandy soils. On the floors of main river valleys shallow sandy alluvial soils exist, which at the mountain foreland are more silty in nature[74].

The character of bedrock is reflected mainly in the grain size composition of soils. A very high percentage of sandy and coarser particles reaching upto 50-80% is a characteristic feature of grain composition of soils over the Darjeeling gneisses as well as Damuda and Daling series (Fig. 3.4). On the steeper slope segments a high content of coarser debris is present. S. Sarkar[75,76] has stated a distinct positive correlation between percent of sandy fraction and slope gradient. The clayely fraction usually don't pass 10% of the total weight (Fig. 3.4). Such mechanical composition of soils has a distinct impact on the water capacity, water conductivity and decide on the subsurface water drainage as well as on deep and intensive leaching of regolith[1,66,76]. In the slope deposits disturbed by mass movements there exist the horizons of various content of silty-clay fraction, influencing changes in the infiltration rate. On the contrary in the tea gardens and on the terraced slopes the spatial differentiation in physical properties of soil is connected mainly with agricultural practices.

The knowledge of physical properties of slope covers, beside their mechanical composition is of essential importance for understanding of

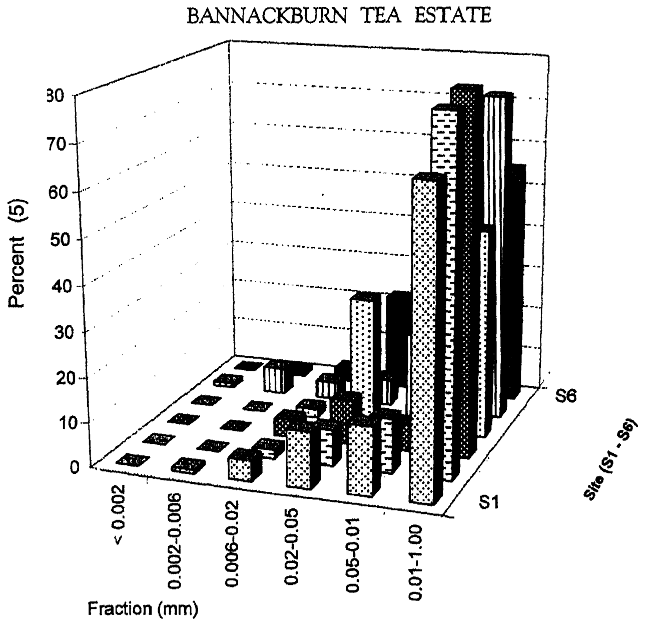


Fig. 3.4: Spatial variability of grain size composition of topsoils at the slope transect from ridge (S1) to valley bottom (S6) in Bannockburn T.E.

water circulation and generation of gravitational processes. During heavy and longlasting rainfalls the full saturation of the soil accelerates the water conductivity and causes a rapid rise of seepage pressure and liquifaction of the soil, facilitating the downward movement.

The water capacity of soils and regolith was determined with the help of the Kopecky's cylinder of 1000 cm^3 in volume each. It was measured for samples of undisturbed structure taken from the stable slopes as well as from slopes transformed by landslides in the Bannockburn TE and Ambootia TE. The samples were taken at every 10 cm depth upto a limit of 1 m.

On the slopes under tea plantation undisturbed by mass movements the total water capacity in samples of the surfacial soil horizon (to 10 cm depth) fluctuated between 35 and 71% of the total soil weight. But over the slopes transformed by gravitational processes the water capacity was higher reaching 46-79%. This means that the soil devoid of its original structure is characterised by higher water capacity. This is probably one of the causes of only sporadic reactivation of colluvial deposits, registered on older gravitation forms[1].

The total water capacity changes also with the depth (Fig. 3.5) being relatively less differentiated to 60 cm depth. But deeper to 1 m it decreases by 25-40% and farther down near the contact with the

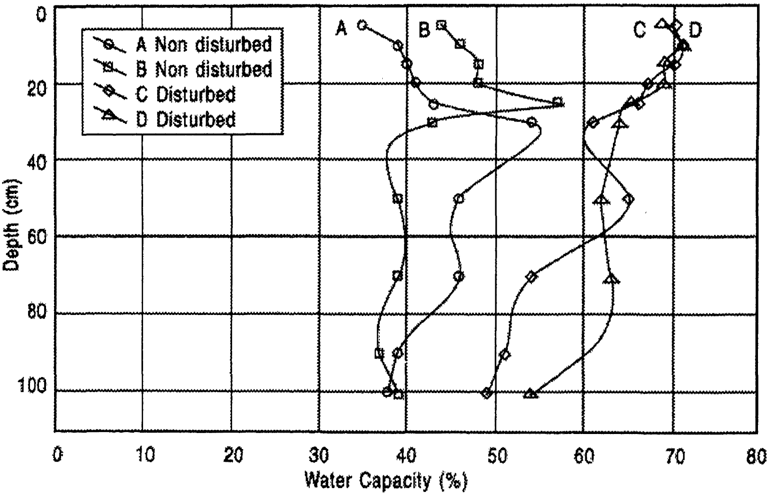


Fig. 3.5: Changes of water capacity of soil column at Bannockburn Tea Estate

bedrock even to 50-60%. In thicker slope deposits consecutive members of different water capacity, mainly controlled by grain size composition were distinguished. The insufficient number of measured samples make impossible a more detail characteristic of water capacity depending on local conditions.

The chemical properties of soil over gneisses are characterised by high content of potassium derived from feldspar and muscovite. These are also poor in lime, magnesium, iron oxides, phosphorous and nitrogen. The soils of the Darjeeling Himalaya have low content of organic matter. Under the forest exist a very thin, below 5 cm Ao horizon typical for this zone. On the tea garden the soil between tea bushes is generally digged up during dry season and other plants are weeded. The aim of these practices is to secure more humidity for bushes at the beginning of rainy season. But this also restricts the enrichment of thin humic horizon Ao. The amount of organic matter measured by loss of ignition in 5 cm thick layer fluctuated between 15 and 37%.

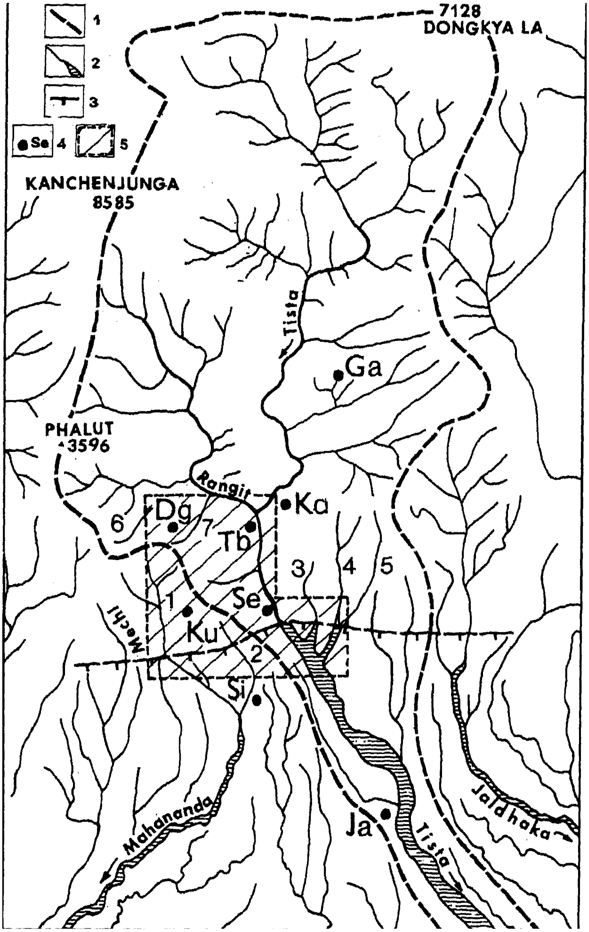
The soil formed over the metamorphic rocks have *p*H from 4.6 to 5.4. Therefore various fertilizers mainly lime are used in the tea gardens. In recent years on several eco-planation the organic fertilisers are being introduced[77].

The forest clearances earlier under the tea plantations and later the formation of narrow terraced fields caused substantial changes in the previous forest slope soil catenas. These are related mainly to decline of water storage and decrease of organic content. Much greater changes in the thickness of soil profile and its physico-chemical properties were done by various mass movements and cultivation over the agricultural terraces. These transformations of slope covers reducing the water storage accelerate the runoff and soil erosion. Therefore most important in these climatic conditions would be the evaluation of sediment budget, of rate of weathering and recovery of soil cover over the degraded slopes.

3.3 Relief

General Features

The Sikkim Himalaya rising in the Kanchenjunga massif up to 8580 meters a.s.l. are dissected by the dendritic valley system of the Tista river. Its catchment area in the mountains exceeds 9350 km^2. Tista after the junction with the right-bank tributary of the Great Rangit gets in the hills only small creeks. The marginal zone of the Darjeeling Hills is deeply dissected to the west by the Mahananda river and its tributary Balasan and to the east by Lish and Gish, joining Tista downstream in the plains (Fig. 3.6 and Photo 1-3).



1. Watershed, 2. Rivers, 3. Boundary of Himalaya, 4. Towns and localities, 5. Area of detail investigations, rivers: 1. Balasan, 2. Mahananda, 3. Lish, 4. Gish, 5. Chel, 6. Jhepikhola, 7. Little Rangit

Ga-Gangtok, Ka-Kalimpong, Tb-Tista Bazar, Dg-Darjeeling, Se-Sevoke, Ku-Kurseong, Si-Siliguri, Ja-Jalpaiguri

Fig. 3.6: Catchment Basin of Tista River

Photo 1: Front of the Darjeeling Himalaya with landslides and alluvial fan covered by dense jungle to the west of Tista valley (by. L. Starkel)

Photo 2: Upper part of the Balasan catchment to the north of Ambootia T.E. Extensive flood plain at the junction of three creeks (by L. Starkel)

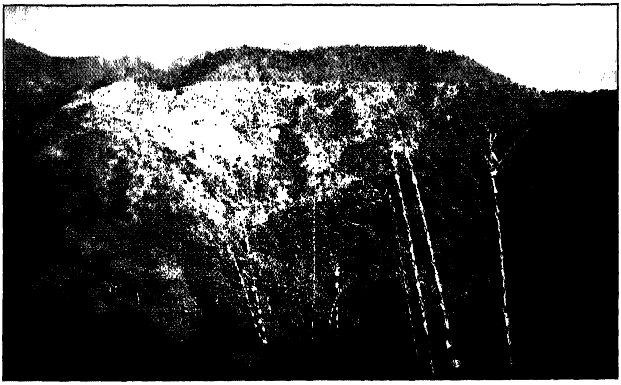
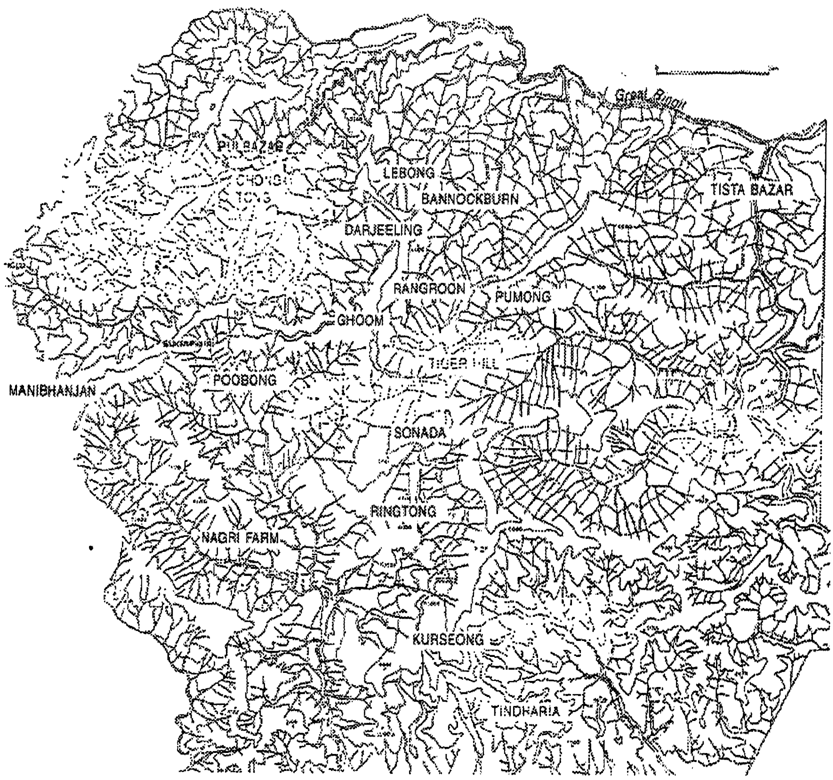


Photo 3: Marginal part of the Darjeeling Himalaya partly still covered by dense forests, east of the Pankhabari Road (by L. Starkel)

The Darjeeling Himalaya are rising directly over the piedmont plain called Terai composed by systems of alluvial fans[43]. The edge of the Hills are dissected with slopes inclined to 30-40° and at a distance of 2 km from the piedmont plain rise to 600 m above it_(Photo 1). The higher ridges of the hog-back type are elevated to 1200 m a.s.l. at 6 km distance and to 2000 m a.s.l. at 12 km. About 25-30 km from Terai continues a W-E elongated ridge (Photo 2), above 2000 m high, culminating in the Tiger Hill (2560 m a.s.l.). Along the western watershed of the Tista this ridge is connected with the foothills of the Kanchenjunga (Sandakphu 3639 m a.s.l.). The relative heights of the Hills fluctuate from 1000 to 2000 meters (Fig. 3.7).



Contours every 300 m

Fig. 3.7: Hypsometric and river network map of Darjeeling region

The network of ridges and valleys has a dendritic pattern. Several narrow ridges fall down at 1500-1800 m a.s.l. in form of structural scarps, connected with the outcrops of more resistant Darjeeling gneisses. Along the main valleys continue flat segments on ridges or flattening over the slope breaks, which mark the vast destructional level.[1] This surface with an elevation of 500-600 m above the river, slopes along the Balasan and other river valleys from 1500 m to 1000 m a.s.l. In all probability it correlates east of the Tista river with the Gorbathan surface covered by rounded boulders and elevated to 700 m a.s.l. and 380 m above the Gish and Chel river[71]. At lower altitudes from 1000 to 600 m a.s.l. (300-200 m over the valley floors) it is noted a lower level, sometimes in the shape of gentle slope bench, rising directly above steep valley sides. Its equivalent at the mountain front are probably flat hills, covered by boulders, of elevation 150-300 m (to 450 m a.s.l.). East of the Tista it is called the Rangamati surface,[71] but also found between the Mahananda and the Balasan[43]. The valley network is characterised by the consequent valleys at the mountain edge, the antecedent Tista and its tributaries of various relations to the tectonic (Photo 4). Many valley reaches follow structural lineaments directed NW-SE or NW-SW[71].

Photo 4: Lowest reach of Great Rangit valley. Gravely bars and slumps on the forested valley sides (1986) (by W. Froehlich)

Slopes

The density of dissection by deep valleys in the Darjeeling Hills is very low and do not reach 0.5 km km^{-2}. This is due to the great depth of valleys and length of slopes reaching 1-3 km and more. Together with tributary valleys over 50 m in depth, the density is never more than double (Fig. 3.7, Starkel[1]). But if we include all the creeks, which incise the slopes no more than several meters, this drainage density is more than double and in the Mahananda catchment it fluctuates between 2.5 and 5.5 km per sq. km[76].

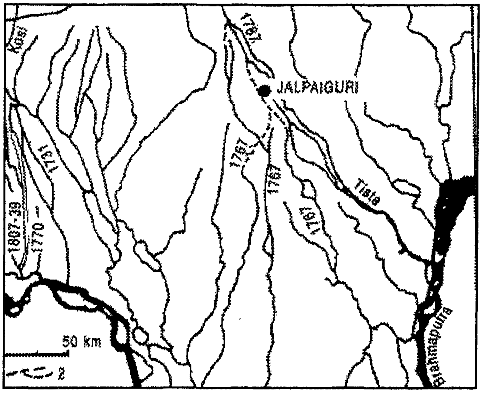
In general young convex slopes with weakly developed concave basal part dominate. Their steeper portions are inclined at 30-45° and are mainly rocky; the more gentle slopes inclined at 15-30° are covered by regoliths. But such simple slope profiles are relatively rare. Very frequently on a single slope there are several scarps and flattening which are mainly structure controlled and rarely reflect an older phase of planation.

Valley Floors and River Channels

The relief of valley floors and river channels exhibits the features of the youthful stage of evolution characterised by steep ungraded channels, narrow floors, steep and undercut valley sides and hanging tributary valleys.

The valley reaches of Tista and Great Rangit rivers, while passing the Darjeeling Hills are characterised by valley floors 100-200 m wide, having straight or sinuous channels with point bars, rare benches of terraces and steep alluvial fans (Photo 4). The valley itself with the gradient of 2‰ has a character of incised sinuous or meandering canyon with vertical undercutting on one or on both river banks. The tributary valleys of the Tista canyon have higher gradients from 2-15%, their headwaters are steeper to 20-30%.

A little different longitudinal profile has the valleys directly dissecting the mountain edge. Among them are the valleys of Balasan, Mahananda, Lish and Gish. Although gradients of headwaters are steep and controlled by lithology and mass movements, as in the Tista catchment, but going downstream, the valley floors start to be broader and aggradation prevails despite the relatively high gradient (Photo 2, 5). Finally these mingle over the alluvial fans in the Terai zone and are either dissected in their apex (like Balasan) or continuously aggrading (like Lish and Gish). The Tista as well the Mahananda



1. Rivers (with date of avulsions), 2. Abandoned channel of Tista from 18th century

Fig. 3.8: Changes of river courses of Tista and Kosi rivers at the Himalayan foredeep (after Sen[124])

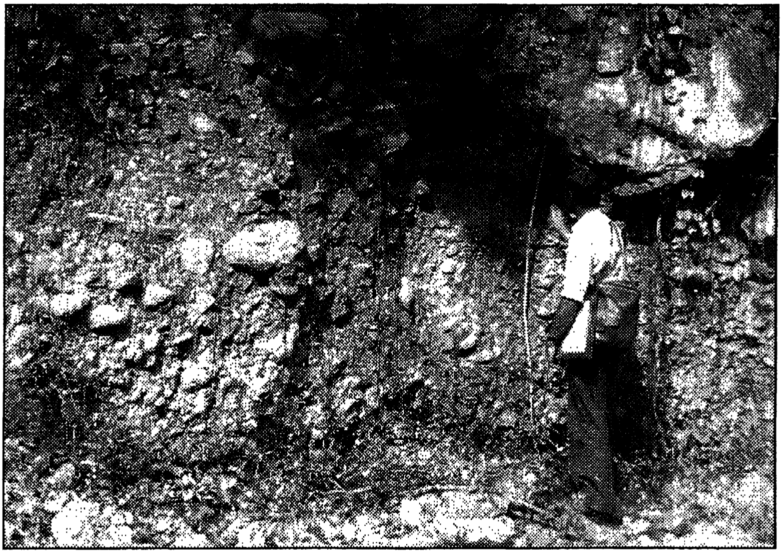


Photo 5: Old debris flow building the terrace of Rangnu river valley (1986) (by W. Froehlich)

are characterised by frequent avulsions during last two centuries (Fig. 3.8).

Evolution of Landscape

The young relief features of the Darjeeling Hills reflect the intensive Quaternary uplift and valley downcutting. The present-day uplift in the marginal part may still reach 3-4 mm per year[78]. But the flattenings document the phases of various uplift rate[23]. The coincidence of these two levels with preserved fragments of elevated fans with boulders of the Gorbathan level and Rangamati level[71] suggest that during relative tectonic stability the aggradation entered upstream into the hills.

In the valley floors exist narrow terrace benches. One of them in the Tista valley, upstream of the Kalijhora creek is elevated upto 40 meters. It is formed of loamy sands and fine gravels indicating the aggradation and delivery of suspended load. The thermoluminescence dating gave the age of the lower part at about 47±6 ka BP and of the upper one at 17±6 ka BP[72] (Fig. 6.11). This indicates that the aggradation followed during the last cold stage of the Pleistocene, when the Himalayan glaciers and alpine belt extended downslope. The dissection of this thick alluvial sequence is the effect of Late Glacial and Holocene. The low terrace upto 15-20 meters high is in the range of present extreme floods[1].

3.4 Climate

The southern slope of the Himalaya lies at the margin of the high-pressure belt where seasonal migration of wind systems alters the weather and rainfall pattern. During winter season the weather is dry and in summer the situation is opposite, when the precipitation are caused by humid air masses from the Indian Ocean carried from SW and S. The summer monsoon starts in May and ends in September or early October. Of special importance are "break phases" combined with heavy and continuous precipitation when the reorganisation of air mass circulation follows[5]. Among most typical feature of these break phases are cyclones rapidly entering from the Bay of Bengal and shift of the monsoon troughs towards the mountain margin.

Beside seasonality the second feature of climate in the Darjeeling Hills is created by the orographic factor, causing the vertical zonality of temperature and other parameters and decline of precipitation moving from the margin to the centre of the mountains. The mountain front is exposed to the heaviest rainfalls, especially the middle parts of southern slopes[28,30,79].

For characteristics of vertical zonality two stations: Dhubri in the plains (26°01'N, 89°59'E, elevation 35 m a.s.l.), and Darjeeling Meteorological Observatory (27°03'N, 88°16'E, elevation 2265 m a.s.l.) were chosen (after Muller[80]). These two points fill the whole vertical diapazone of the discussed region (Figs. 3.9 and 3.10).

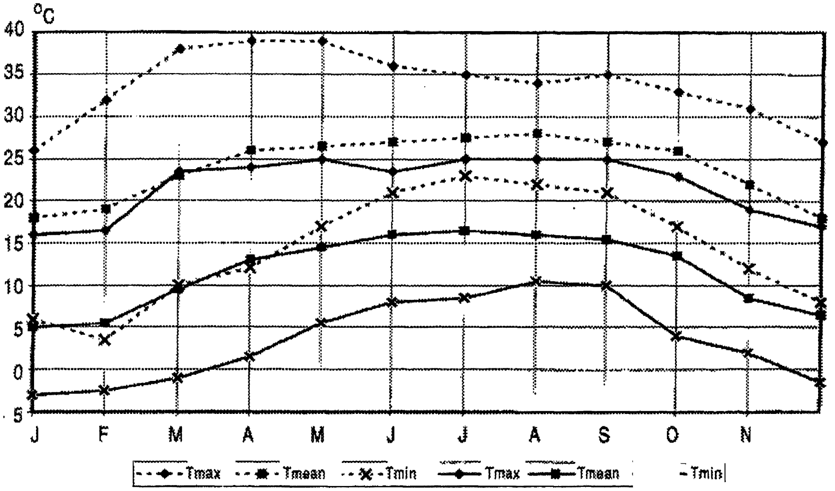


Fig. 3.9: Annual course of temperature in Darjeeling (above 2100 m a.s.l.) and in Dhubri (in the plains) – mean, maximum and minimum in the period (after Landsberg[154])

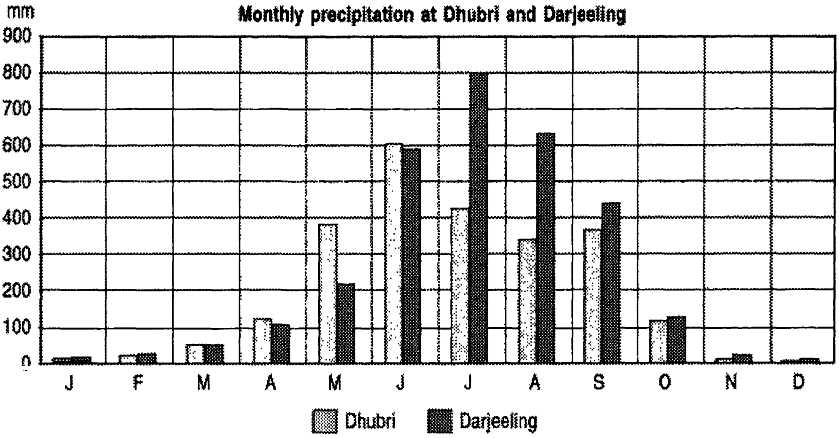
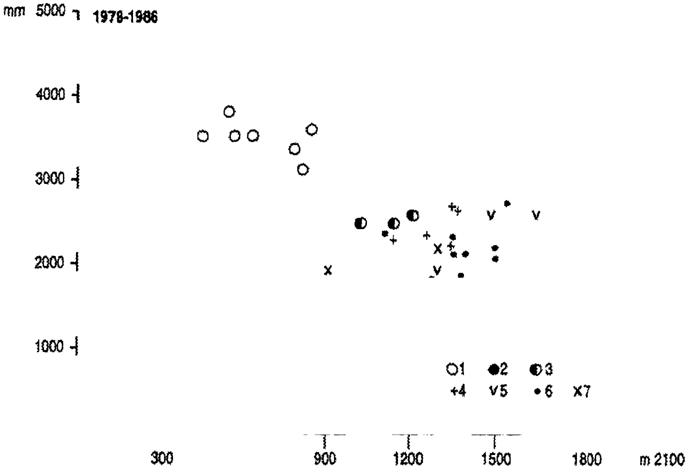


Fig. 3.10: Mean monthly rainfalls in Darjeeling and in Dhubri (after Landsberg[154])

The mean annual temperature fluctuate from 24°C in the plains and drops below 12°C on the ridges. During summer months (VI-IX) mean temperatures reach 27-28°C in the plains and fall to 16-17°C in Darjeeling (absolute max. 25°). In winter the lowest temperature drops to 12-13°C, when on the ridges mean temperature of winter months (XII-II) fluctuates between 5-6°C with lowest recorded temperature ranging from -1 to -5°C. The air humidity fluctuates in the plains from 58% in winter to 87% in summer, but in Darjeeling is always very high (80% in winter and 95% in summer). Therefore the cloudiness in the hills is very high. Practically in every afternoon the main ridges are covered by clouds.

The annual precipitations fluctuate from 2000-2500 mm in the plains to 4000-6000 mm at the mountain front and then decline to 2000 mm north of Darjeeling (Fig. 3.11 and 3.12). About 400 mm only is recorded in the upper Sikkimese part of the Tista basin. Depending on which of the stations in Darjeeling was selected (there exist at least 3 various stations) and the period considered, the mean annual precipitation fluctuated from 2562 mm (Planters Club for 1949-1986) to 3037 mm[80]. There is a distinct seasonal distribution of rains. It fluctuates from several mm in winter months upto 400-800 mm every month in summer. The number of days with rain (>2.5 mm) varies from below 100 in the plains to 124 in Darjeeling (among them 102 from May to September).

There is no distinct relation between total rainfall and altitude (Fig. 3.11). The southern slope of first ridge gets much higher annual precipitation (4000-5000 mm, at Mission Hill east of Tista valley above

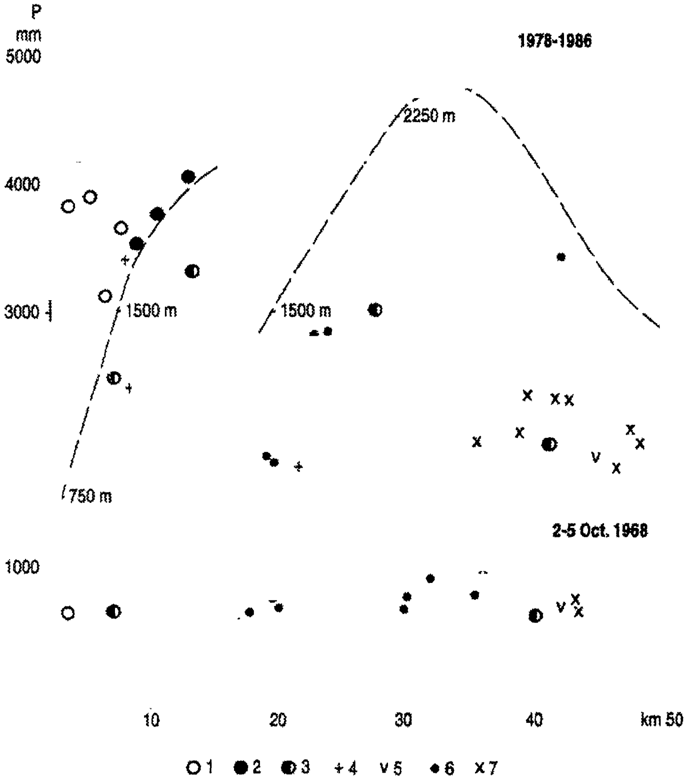


Position of stations: 1. Southern marginal slope, 2. Ridges on southern margin, 3. Other locations on ridges, 4. Northern slopes in southern margin, 5. W- and E- exposed slopes, 6. S-exposed slopes in the interior, 7. N-exposed slopes in the interior

Fig. 3.11: Annual rainfall totals between 1978-1986 in relation to the altitude above sea level

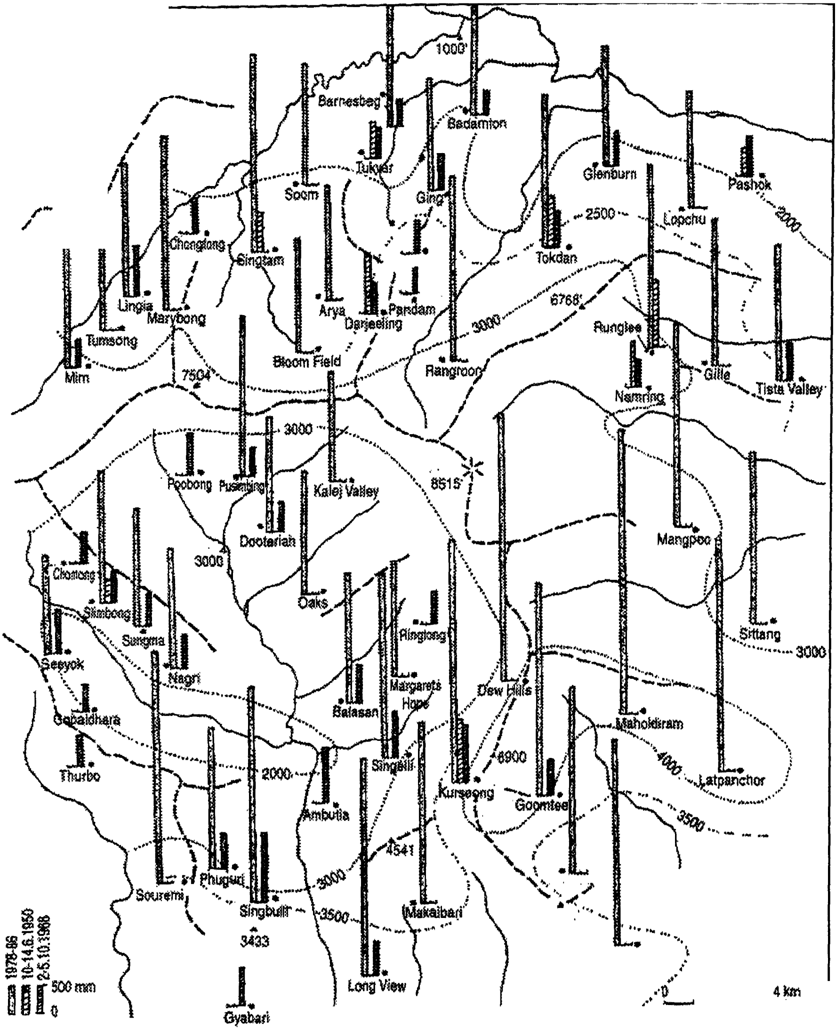
6000 mm) (Fig. 3.12). Then on the lee side the mean precipitation drops to 2000-2500 mm. The next main ridge with Tiger Hill gets 3000 mm and to the north in the Great Rangit valley rainfall even below 2000 mm is recorded.

The enclosed map (Fig. 3.13) elaborated for the period 1978-1986 is based on about 60 rainguages located mainly in the tea gardens. It shows the role of the mountain barriers as well as the role of great Tista valley transversally located to the east, where the rain-shadow effect is not so distinct. It is characteristic of this region that the extreme continuous rainfalls exactly repeat this areal rainfall pattern (Fig. 3.12).



Symbols as on Fig. 3.11. Two curves indicate the marginal scarp near Kurseong and main latitudinal ridge near Ghoom with Tiger Hill

Fig. 3.12: Rainfall totals in 1978-1986 and during continuous rain in 1968 with the growing distance from the mountain front (0-50 km)



In addition the totals of extreme rainfalls in June 1950 and October 1968 are presented

Fig. 3.13: Map of annual rainfalls in the Darjeeling region (mean values for 1978-1986)

3.5 Natural Vegetation

The configuration of the mountains and the impact of strong moisture laden monsoon winds from the south, greatly influence the character of the vegetation from place to place. The outer spurs have a heavy rainfall and are densely clad with moist forest of tropical, subtropical and temperate types. But the valleys and gorges further inside have a lower rainfall and tend to bear a drier type of forest communities.

The variation in rainfall aspect even over comparatively smaller areas has considerable effect on the distribution of the species and the composition of the crop. Thus in the valley, forests of *Shorea robusta* grow on the ridge and on southern aspects, whereas on northern slopes at same altitude mainly miscellaneous species are found. Similarly in the Rangit valley at Badamtam where the rainfall is low (2000 mm), *Pinus longifolia* appears on the ridges and on the southern aspect, whereas this is absent on the northern aspect. Again, at Ramam where rainfall is less than occurring further east, *Tsuga brunoniana* appears in compact patches particularly at Ramam and on Saberkum ridge, whereas it is absent in other areas further east.

Consequently the following five altitudinal zones of forest can be distinguished in the Darjeeling Himalaya[81-83].

Forest types		*Altitude*
1	Tropical moist deciduous	300–1000 m
2	Tropical evergreen lower montane	1000–2000 m
3	Tropical evergreen upper montane	2000–3000 m
4	Temperate coniferous	3000–3500 m
5	Sub-alpine forest	above 3500 m

Tropical Moist Deciduous Forest (300–1000 m)

Shorea robusta remains the most prominent species and the undergrowth is quite dense. *Shorea robusta* attains a height upto 20-30 m. Towards the east, the leafless period is gradually reduced; but the higher density of undergrowth, the competition by the evergreen species, reduce the chances of regeneration of *Shorea robusta* to a point, where the dominance of sal can only be achieved by forest management. Sal is confined to the ridges, spurs and on the southern aspect in the Tista and Great Rangit valleys and also in Goke forests (Photo 1-3). Sal reaches higher altitudes on southerly aspect than on the northerly ones. Climbers are numerous and form impenetrable masses in the wet mixed forest. The commonest species includes Chapalish (*Artocarpus chaplasha*), Borhar, Kawla (*Machilus Sp.*) Lali (*Amoora wallichii*), Ambaake (*Jambora formosa*) etc. For sal a clearly defined dry season is a necessity. *Shorea robusta* thrives even under heavy precipitation as long as there is a dry season. But the species does not thrive where there is moderate precipitation throughout the year, without a dry season. Topography is of importance only as far as higher rainfall is concerned, but more important is a well-drained soil. The impact of man leads to (secondary) savannas, but man exercises deliberate influence to propagate the dominance of *Shorea robusta* and therefore more or less pure forests are found at places, where the growth of its associates is checked by periodic burning.

Tropical Evergreen Lower Montane Forest (1000-2000 m)

The dominant species are mainly evergreen, but distinctly different from the tropical rain forest. Under favourable conditions, the forest attains upto 50 m height, generally their height varies between 20-30m. The canopy normally is less closed compared with the tropical rain forest, the outstandingly high trees usually do not appear next to each other. There is a well-developed middle storey and also undergrowth of shrubs. Tree ferns are well represented. The dominance of *Quercus* and *Castanopsis* is a striking characteristic. Conifers such as *Podocarpus* are only locally met with. The transition towards this montane forest is always indicated where *Castanopsis* appears above *Shorea robusta.* Precipitation amounts from 1500 to 5000 mm depending on slope exposure, there is less distinct dry season. During winter, there is frequently heavy dew instead of rain, accompanied by dense fog. Humidity is always high and temperature even. Owing to these conditions the montane forest covers steep slopes almost everywhere, provided there is good drainage. Along the water courses *Alnus nepalensis*, is typical, on steep crests *Pandanus furcatus* predominate. Plantations in this zone are extensive and consist mainly of Dhupi (*Cryptomeria japonica*). The impact of man is conspicuous in so far, as within the range of this type are Tea and Cinchona plantations. On abandoned sites, a secondary growth of *Maesa chisia, Rhus semialata, Alnus nepalensis, Schima wallichii* is wide spread.

Tropical Evergreen Upper Montane Forest (2000-3000 m)

A dense evergreen forest, upto 30 m high, it usually has a closed canopy; branches and trunks are thickly wrapped into moss. An astonishing number of epiphytes find suitable living conditions here. According to H.G. Champion[81], the swaying mosses and lichens garlands, together with the ever present veils of the mist and fog which gives these forests a rather eerie appearance. Usually the stands are mixed, but there is always a strong tendency to the prominence of a few: *Quercus* and

Lauraceae from 1800-2000 m high up, almost pure stands of *Rhododendron* in between 2500-2800 m. The *Magnolias* when in blossom are exceedingly beautiful, though numerically they are of minor importance.

The climatic records of Darjeeling show that there is precipitation during most of the year, specially heavy June to August, comparatively low in November to March (heavy dew). High humidity together with dense fog, characterise these forests; consequently there is not much direct sunshine. The trees are stag-headed and covered with moss and lichens. Undergrowth is dense and contains many Nettles, Raspberries, Ferns and Bamboos. Plantations in this zone are extensive and consist mainly of Dhupi (*Cryptomeria japonica*).

The soil rich in rock debris makes no difference to the vegetation in view of the very high rainfall. On slips *Alnus nepalensis* appears as a pioneer; open steep ridges are frequented by Rhododendron and bamboo thickets.

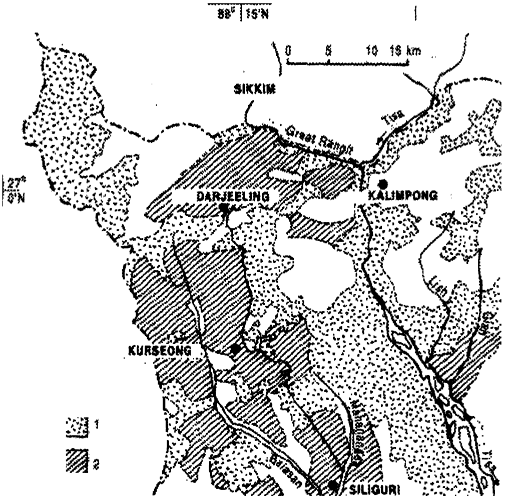
3.6 Land Use Changes and Population Pressure

In 1829 General Lloyd visited first the Darjeeling Hills. On1st February 1835 by a deed of grant by the Raja of Sikkim. Darjeeling was ceded to the East India Company. At the onset it was a totally forested mountain tract inhabited by about 100 souls of the Lepcha population west of the Tista river upto the Great Rangit river to the north (about 320 km^2). With the establishment of army barracks and sanatorium for ailing British soldiers, a small settlement of Darjeeling was founded and in 1840 the military Pankhabari Road[84] was opened. During 1850 - 1860 with the expansion of tea plantations, the main Hill Cart Road was constructed in 1869 and then in 1879-1881 the railway line was extended from plains upto Darjeeling. The tea boom was a basic cause of the population growth, mainly of the Nepalese immigrants. The second half of 20th century is marked by extending deforestation, abundance of many tea gardens and expansion of population. At present less then 38% of the total area is under forest, 37% occupied by the agriculture land and 22.5% is under tea gardens.

Conditions of the Forest

Prior to 1863 very little attention was paid to conservation and during 1872-1873 conservation of forests received its first impetus, though the law had already been there since 1865. Upto 1879 Darjeeling district had 11,000 ha of Reserved Forest. However, during this period there was a heavy demand of sleepers for railways and exploitation started from 1874-1875. But, the Britishers made it clear that forest at the watershed portions of the mountains should not be brought under commercial exploitation as it will surely create ecological hazard. Again after independence there was an unprecedented demand for timber. It is in this context that the upper belt of forest was taken for commercial use. There was a desperate attempt to cut trees, without taking care of soil erosion, water supply or landslips. In 50's and 60's plantations were created with increasing emphasis on Sal and Teak. But these two indegenous varities were discarded in the 70's and quick growing Eucalyptus was emphasised. But Eucalyptus takes more underground water than Sal.

Much of the natural forests in the accessible areas in Senchal, Ghum-Simara and Takdah Ranges have already been converted and among the forest blocks still retaining natural forests (Photo 3), the density of the crop is moderate in Rishop, Barasenchal, Lopchu, Rongbong and Durbin blocks. The rest of the natural forests still remaining are situated in some cases on difficult terrains. As a result of choosing the best areas for clear felling during the last few decades, the standing crop is poor. Trees have become mature and quite a good percentage is found to be of defective quality. Natural reservation is



1. Main forest areas, 2. Tea gardens (in about 50-70% under tea plantations)

Fig. 3.14: Map of forests and tea gardens in the Darjeeling Himalaya and its foreland

in deficit. Moreover due to excessive grazing and heavy undergrowth of bamboos very few of them survive and establish itself. Now a days the reserved forest is concentrated in two belts: above 1500-1800 m a.s.l. and below 600 m a.s.l. (Fig. 3.14).

In 1901 about 51.54% of the total area of the Darjeeling district was covered by forest. In 1921 it was 49.14%, in 1931 - 45.46%, in 1941 - 45.08%, in 1951 - 45.01%, in 1961 - 40.07%, in 1971 - 38.03%, in 1981- 38.2%[85] (Fig. 3.15 and Table II). Such gradual depletion of the forest has a close link with the simultaneous increase in population in this part of India. The pressure on land and the search for fuel cause an indiscriminate felling. This has its consequences in soil erosion, reduction in ground water storage and other disasters. It has been estimated that 70% of the cooking energy needs of the rural population is still being met by fire wood and this practice is likely to continue, if they are not provided with an alternate cheap source of energy.

The official data about the present situation of forest in the Darjeeling Himalayas is often misleading in the sense that, in actuality

Table II: The forest area and density of population in the Darjeeling district

Year	Total area (km²)	Total population	Per capita forest area (ha)
1901	3015	249117	0.62
1921	3015	282748	0.52
1941	3087	376369	0.37
1961	3108	624640	0.23
1981	3149	1024269	0.12

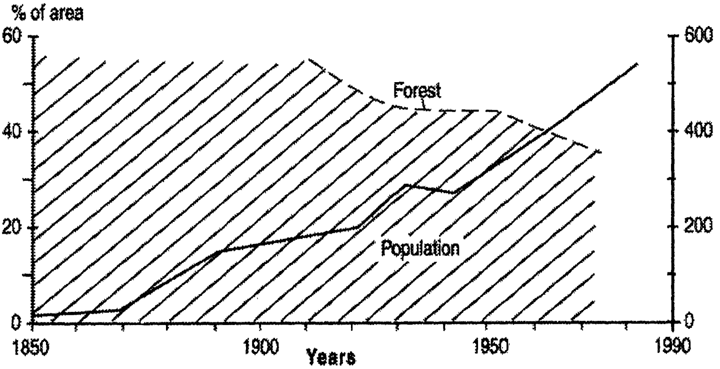


Fig. 3.15: Increase of population and extension of deforestation in the Darjeeling Himalaya between 1850 and 1980 (after Working Plan of Darjeeling Forest Division[157])

the present cover is only 10 to 15% of the total area. This information has been gathered from local fieldwork and experience.

Tea Gardens and Agriculture

In 1840, Dr Campbell started the first experiments with imported tea bushes. In between 1852-1857 the first four tea-gardens near Darjeeling were founded. Their number in 1866, reached 39 and till the beginning of 20th century passed 150 occupying most of the gentle slopes upto the gradient of 15-25° and the elevation 2000-2100 m a.s.l. (Photo 6). Since the Second World War the area under tea and the tea production had been reduced considerably by about 50%. The number of tea gardens decreased to about 75. Many of the tea estates have been abandoned due to various reasons, one of them is the soil-loss during catastrophic rainfalls (Photo 7).

At the tea gardens the Nepalese immigrants are employed. The villages of these residential labourers are now overpopulated, there is no room for their gardens and further housing. They should be supplied with free firewood by tea garden owners. Therefore in last few decades the patches of jungle are disappearing rapidly and steep slopes are taken under housing or terraced fields.

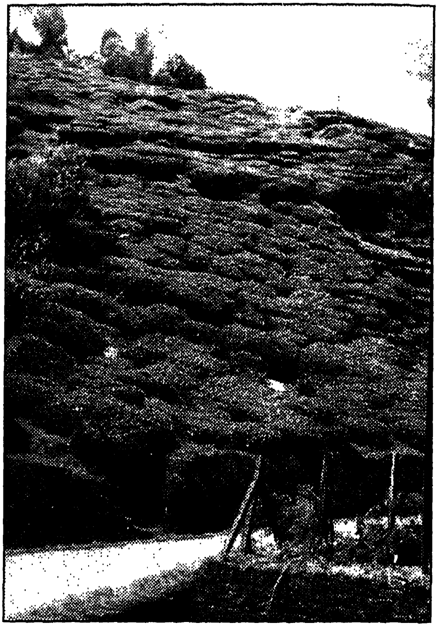


Photo 6: Bannockburn Tea Garden. Visible scarps affected by slumps and earth-flows in October 1968 (1986) (by W. Froehlich)

The abandoned tea gardens and other deforested areas occupy now upto 37% (in 1901 less than 20%) of total area. Till now, people practice slash and burn system of cultivation called "jhum". Over these cropped areas with terraced fields mainly maize, potato, millet, paddy, cardamon, ginger as well as vegetables like sqash, radish, peas, beans, cabbage and others are grown[86]. In lower altitudes the plantation of orange tree is very frequent.

In last decades these terraced fields using "jhum" techniques expanded over the slopes close to the Nepal border. Most of the crops are consumed by villagers but with rising population in the towns there is a visible tendency in the villagers to sell those in the market. The parallely growing number of cattle creates the problem of fodder, and overgrazing still continues in the forested areas.

Photo 7: Deforested tributary valley with active gully and remains of jungle on steep slopes in Bannockburn T. E. (1986) (by W. Froehlich)

Population Growth and Urbanization

During the early stage of the tea garden foundation (in 1869) the population of Darjeeling Hills did not exceed 22 thousands inhabitants (Census Handbook 1981). Later the continuous growth was accelerated twice: in 1920-th and after the independence of India (Fig. 3.15). The population of the hilly areas through immigration either exceeded or is reaching one million inhabitants according to various sources. An exceptionally high growth is observed in the towns and market villages, where the percent of the Bengali and Nepali population is rising rapidly in last decades. This is also the effect of great demographic pressure from the overpopulated plains in Bengal, Bangladesh and Nepal. In the towns like Darjeeling or Kurseong, located on the mountain ridges with steep slopes, there is a great shortage of land[87] for building and road constructions. Many new constructions and roads undermine the slopes, which are exposed to landsliding during heavy rains.

The problems of the forecasting and expected ecological catastrophe will be discussed in the final chapters[88-90].

4
RAINFALL CHARACTERISTICS

The knowledge of rainfall pattern in time and space is fundamental for the understanding the mechanism of run-off and of thresholds of slope stability. Therefore, after enumeration of the characteristics of annual course of rainfalls and days with rainfalls will follow a description of duration of rains, probability of maximum diurnal and 3-day rainfalls, rain intensity and typology of heavy rains including their frequency and characteristics of several single events[91].

The annual totals of rainfall in Darjeeling town fluctuate between 1870 and 3690 mm for the period 1949-1986 and in Ambootia TE (mean totals 3140 mm) between 2550 and 3900 mm for the period 1964-1989. These deviations are relatively low and do not exceed 25-30% during extreme years (Fig. 4.1).

The annual course of rainfall is well illustrated by the cumulative curve (Fig. 4.2) and days with rains (Fig. 4.3). Beside a few showers from January to March the rainy season starts from mid-April, but till the end of May rains are not heavy and their totals (I-V) vary from 100-300 mm. Then till mid-September rain falls mainly every day and

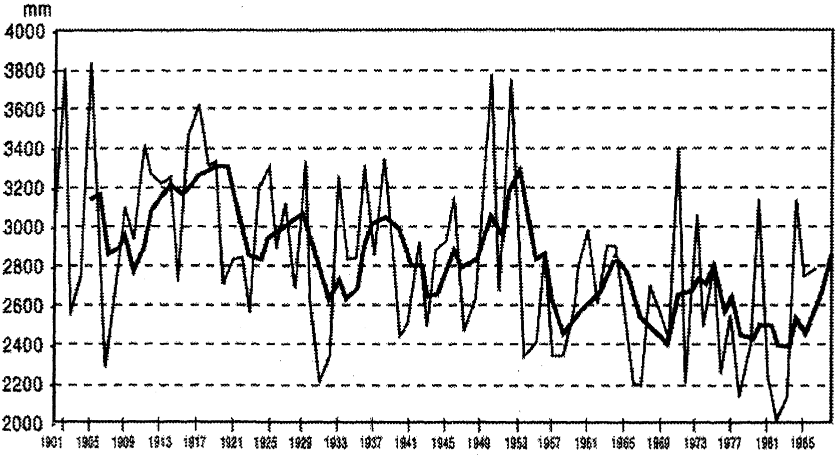


Fig. 4.1A: *Annual rainfall in Darjeeling (1901-1988) and mean 5 year moving average*

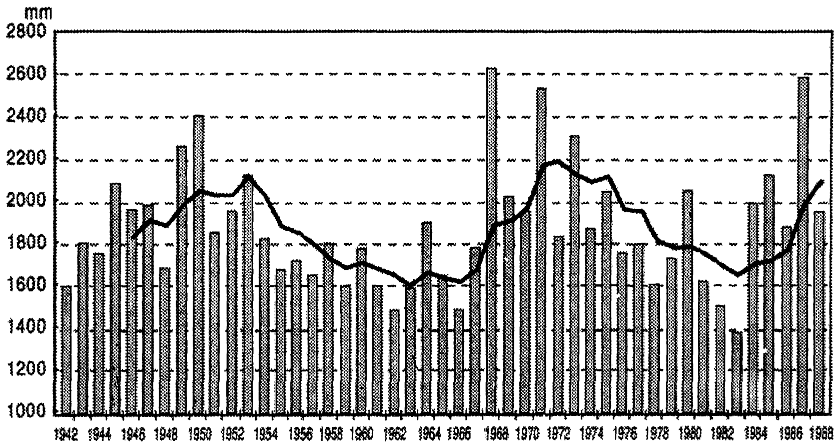


Fig. 4.1B: Annual rainfall in Pashok T.E. (1942-1988)

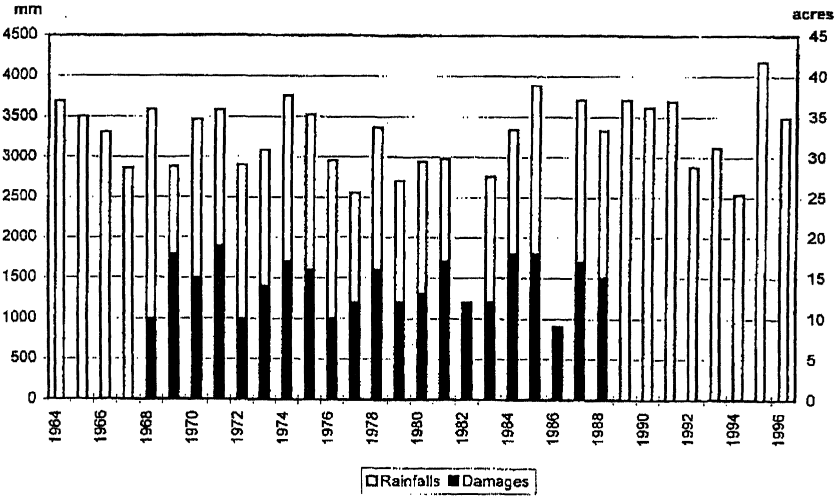
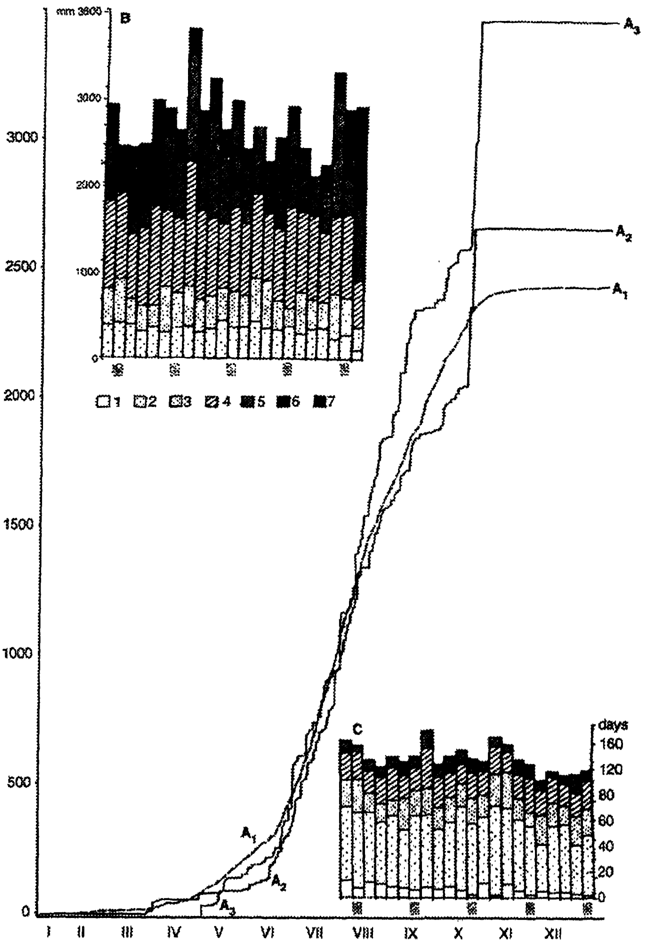


Fig. 4.1C: Annual rainfall in Ambootia T.E. (1964-1996) and landslide damages in acres indicated in the reports (records for 1982 and 1986 are missing)

monthly totals fluctuate between 300 and 800 mm. Most unstable is October, which may be dry or may have heavy precipitation. The last 80-100 days usually remain dry.

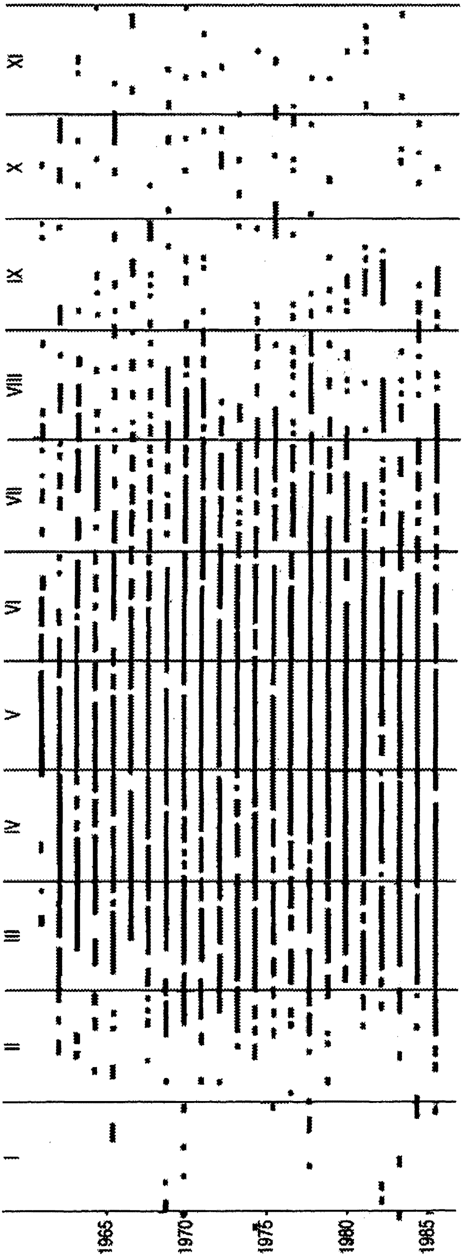
Among 120-170 rainy days (Fig. 4.2) in particular years 45-80 days are characterised by rainfalls of 1-10 mm, the days with rain above 20 mm are 30-60 and above 50 mm about 5-15 days. From Fig 4.2 it is seen that between 20 and 70% of water may be delivered by rainfalls above 20 mm per day.



A–Mean cumulative curve 1964-1986 for Darjeeling (after Froehlich *et al.*,[65]), A2–Cumulative curve for Darjeeling in 1968, A3–Cumulative curve for Ambootia in 1968, B. precipitation totals classes of daily rainfall for Darjeeling. C–Number of days with rainfalls of various totals: 1. 0-1 mm, 2. 1-10 mm, 3. 10-20 mm, 4. 20-50 mm, 5. 50-100 mm, 6. 100-200 mm, 7. above 200 mm

Fig. 4.2: Rainfall distribution in Darjeeling

From the hydrological point of view very important is the duration of rainfalls. A simple measure of that is the number of consecutive rainy days with daily rainfall above 20 mm. Some deeper infiltration, feeding of groundwater or some overland flow may be expected during such rain. The characteristic of such consecutive rainy days for Bannockburn TE shows at least 5-10 events with consecutive 2 and



One day breaks are not indicated

Fig. 4.3: Rainy days registered at Darjeeling Planters Club from 1964 to 1985 (after Froehlich et al.[65])

more rainy days every year, as well as once in 3-5 years at least 5 consecutive days with rainfall above 20 mm.

The knowledge on the intensity of rainfall is insufficient. But from the pluviogram of the continuous rain in October 1968 the intensity during 3-4 hours is known[1,92] to be 1 mm min^{-1} and similar values were measured during several downpours in 1987 at Bannockburn TE. But H. Chandra[92] mentioned the highest recorded intensity during 10 minutes to be about 12.5 mm per minute, which is difficult to accept. H. Chandra[92] also counted 40 days with rainfalls above 250 mm between 1891-1965 in Darjeeling region. According to A.J. Dash[93] in 1940 in Darjeeling 520.7 mm was recorded in one day and in 1942 about 900 mm in about 40 hours.

A relatively good measure of the frequency of extreme events is the probability of the maximum diurnal rainfall and of 3 day continuous rain[94]. The mean highest rainfall in 24 hours in Darjeeling (for period 1949-1986) reaches 172 mm and it fluctuates between 70 and 520 mm[91]. Every 5-th year it crosses 200 mm (Fig. 4.4). Rains lasting for 3 consecutive days reach 250 mm every second year and 320 mm every 5-th year. In 1950 it was recorded 960 mm. It was not proved that all of them had continuous character.

B Biswas and C.V. Bhadram[53] analysed the rainstorms of 1, 2 and 3-day duration covering large part of the Tista basin and passing the average depth of 40 mm in one day and 80 and 120 mm in 2 and 3 days respectively. On the basis of that criteria 53 storms in the period between 1960 and 1981 were analysed. Among them there were 11 rainfalls of 2-day duration and only 2 were of 3-day duration.

Among heavy rainfalls in the Darjeeling Himalaya two main types of heavy rainfalls which differ in their totals, intensity, duration and effects were distinguished[3,94].

Heavy downpours of duration upto several hours and high intensity is restricted to small areas. On the other hand continuous rains lasting two, three, upto five days of various intensity and totals from 250 to 1200 mm cover large areas (usually the whole Darjeeling Hills, even the most of Sikkim Himalaya or their large portions).

Heavy Downpours

The knowledge of heavy high intensity downpours is insufficient. One well recognised was a downpour of several hours long on 17th July

1988 when several gullies and debris flow in the neighbourhood of Kurseong were reactivated. This downpour covered an area of 30x20 km (Fig. 4.5). The heaviest rain of 304.8 mm was recorded at Singell TE and in Kurseong 203 mm. Several days later similar heavy rain of 239 mm was recorded at Takdah TE (being not recorded at 3 other stations at 3-5 km distance).

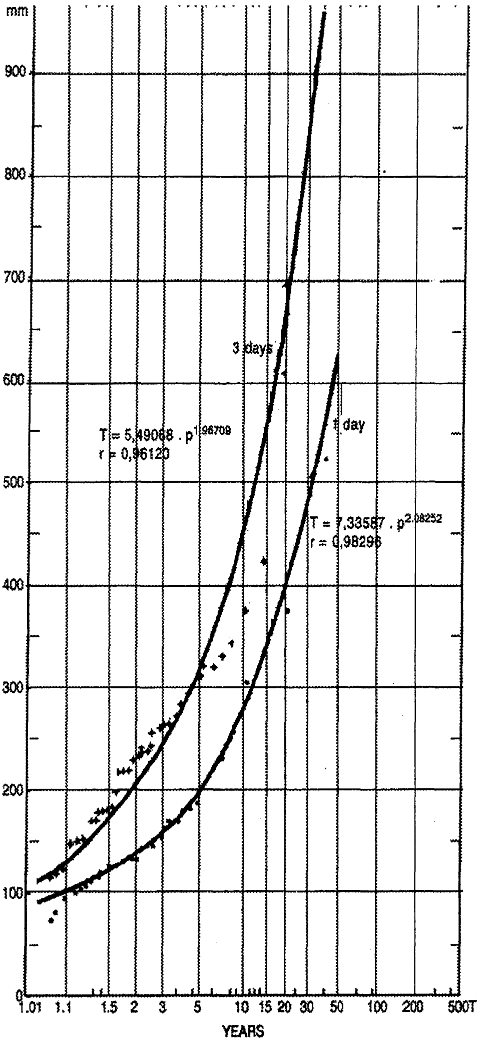


Fig. 4.4: Recurrence intervals for maximum rainfalls at the Darjeeling Planters Club: (1949-1986); one day and 3 consecutive days (after Froehlich et al.[91])

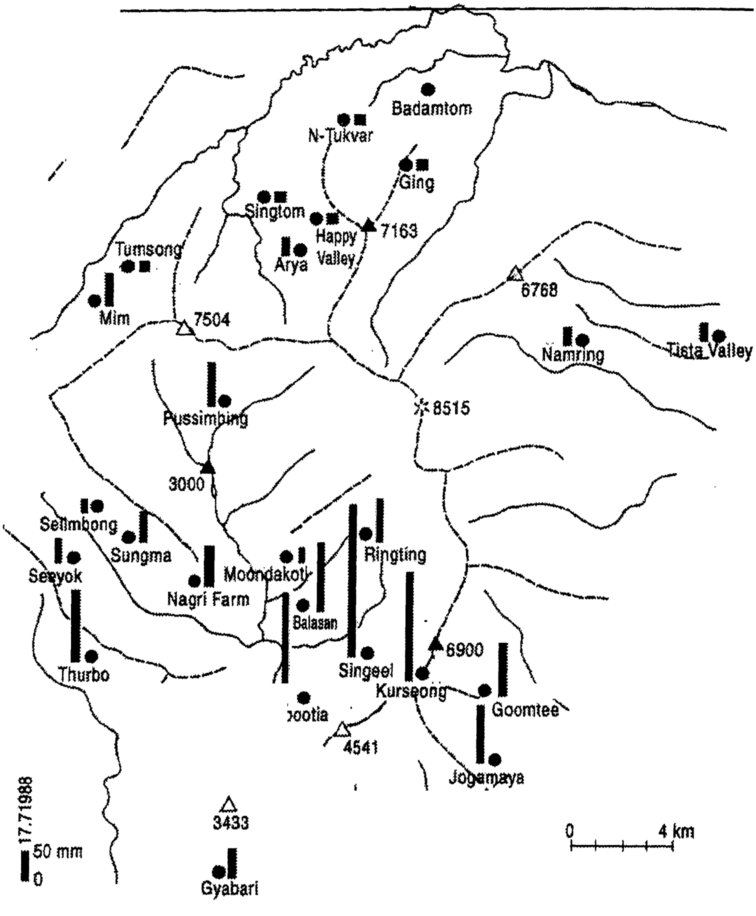


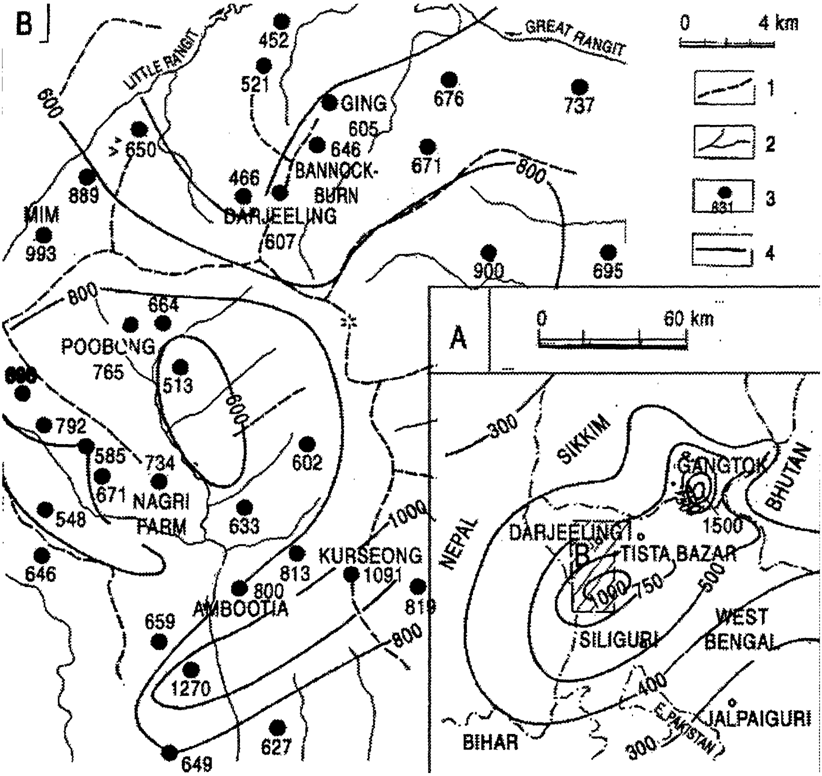
Fig. 4.5: Rainfalls during heavy downpour on 17 July 1988, near Kurseong

Continuous Heavy Rains

The recognition of such rainfalls is relatively good, as these are associated with damages caused by floods and landslides. Various sources mentioned about longlasting rains and floods in 1787-1789 and 1827. But the first recorded continuous rain at 24-25 September 1899 at Darjeeling was 609 mm (493 mm in one day). Happy Valley TE recorded 691 mm.

The next continuous rain of 965 mm was recorded during 11-13 June 1950 at Darjeeling and on last day 520.7 mm (rain in the Hills started on 10th and ended on 14th). Kurseong noted in 36 hours (9-10th) upto 960 mm. The heaviest recorded rain reached 1200 mm.

The last catastrophic rain happened at the end of the rainy season (Fig. 4.2) between 2nd and 5th October 1968 and has been described in details by several authors[1,52,53,95,155]. The rain was caused by deep cyclone coming from the Bay of Bengal. The rainfall covered extensive areas of the Sikkim Himalaya, Eastern Nepal, Western Bhutan and the mountain foreland. One centre near Kurseong, St. Mary College recorded 1091 mm (after Dhar *et al.*,[30] other station noted 1780 mm) and the second near Gangtok and Pedong recorded upto 1500 m (Fig. 4.6). The other centre was located near the Assam border. Over the area of 5180 km^2 the mean total rainfall reached 650 mm[30]. The rainfall distribution in space followed the mean annual course (Fig. 3.13), e.g. southern slopes were getting more rain (Fig. 3.12).



A-Rainfalls in Sikkim Himalaya[155], B-Rainfalls in Darjeeling region (after data collected from tea gardens), 1. Main ridges, 2. Rivers, 3. Rainfall totals, 4. Isohyets

Fig. 4.6: Areal distribution of precipitation during continuous rain at 2-5 October 1968

The clouds moved from the mountain foreland, following the transverse direction of valleys. On the basis of two pluviograms from Nagri Farm and Kalimpong (Fig. 4.7) it is known that the intensity during more than 45 hours fluctuated between 3 and 20 mm per hour and closely to the end during 4 hours at evening the 4th exceeded 35-50 mm h^{-1}. Afterwards the intensity decreased to 3-10 mm.

Between 1950 and 1968 several events with 3 consecutive rainy days were recorded. Among these 421 mm in 1952, in 1959-309 mm and 317 mm in 1966 were noted in Darjeeling.

Information on continuous rainfalls which never reached the level of October 1968 and were not so extensive in space, but locally were responsible for the rising of water level in streams as well for triggering mass movements were available after 1968.

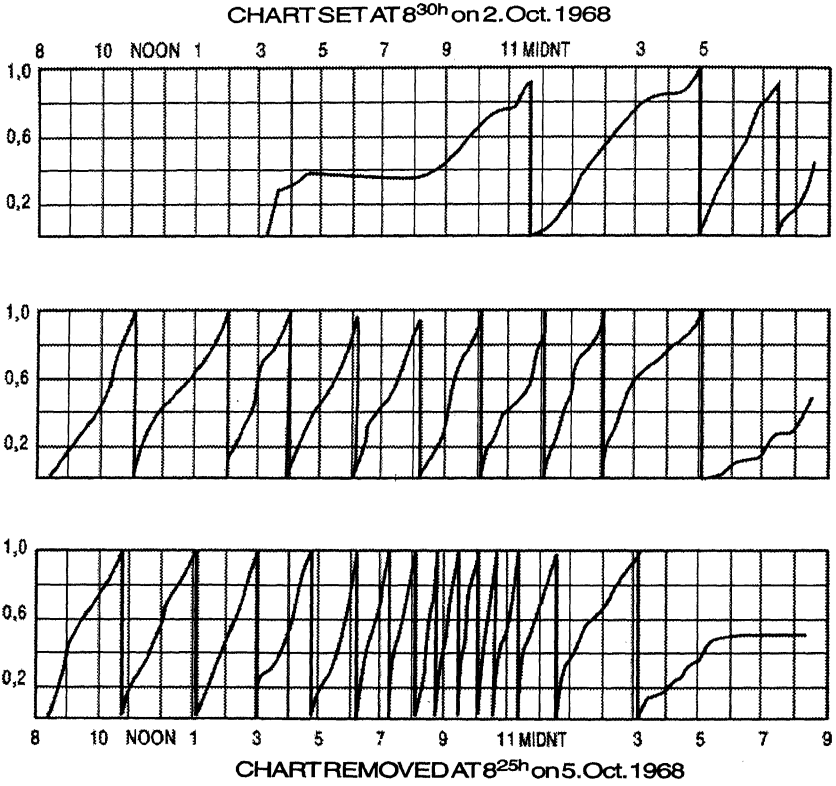


Fig. 4.7. Pluviogram from Nagri Farm Tea Research Station 2-5 October 1968 (by permission of Dr F. Rahman, from Starkel[1])

On 11-12 October 1973 between 90 and 580 mm was recorded. Next year between 1 and 3 July in the region east of the Tista valley the total rainfall exceeded 600 mm. between 3 to 5 September 1980 mean rainfall fluctuated between 100 and 250 mm but locally 515 mm was recorded.

Next heavy rains on 26-28 June 1983 were restricted to the area between Darjeeling and Takdah TE where it was recorded 382 mm. From 16 to 17 October 1985 it rained over an extensive area. The total rainfall fluctuated between 50 and 500 mm, (Ranglie-Rangliot recorded 561 mm). On 9-11 September 1986 similar continuous rain was recorded up to 457 mm (Singell TE). The following year between 9-13 August rains covered large areas and their mean total fluctuated between 300 and 600 mm (Gyabaree TE recorded 692 mm). After 1987 the continuous rainfalls were not so pronounced. Only the local reactivation of landslides turned our attention to continuous rains. Such rains were recorded in an elevated tea garden Ranglie-Rangliot, where in 1990 first 350 mm in 4 days was recorded and after several weeks 600 mm in 7 days.

In any case, during the last 100 years rainfall passed 600-1000 mm in 2-3 days on large areas only on three occasions.

5

MECHANISM OF SLOPE PROCESSES AND THEIR EVOLUTION

5.1 Typology of Slope Processes and Forms

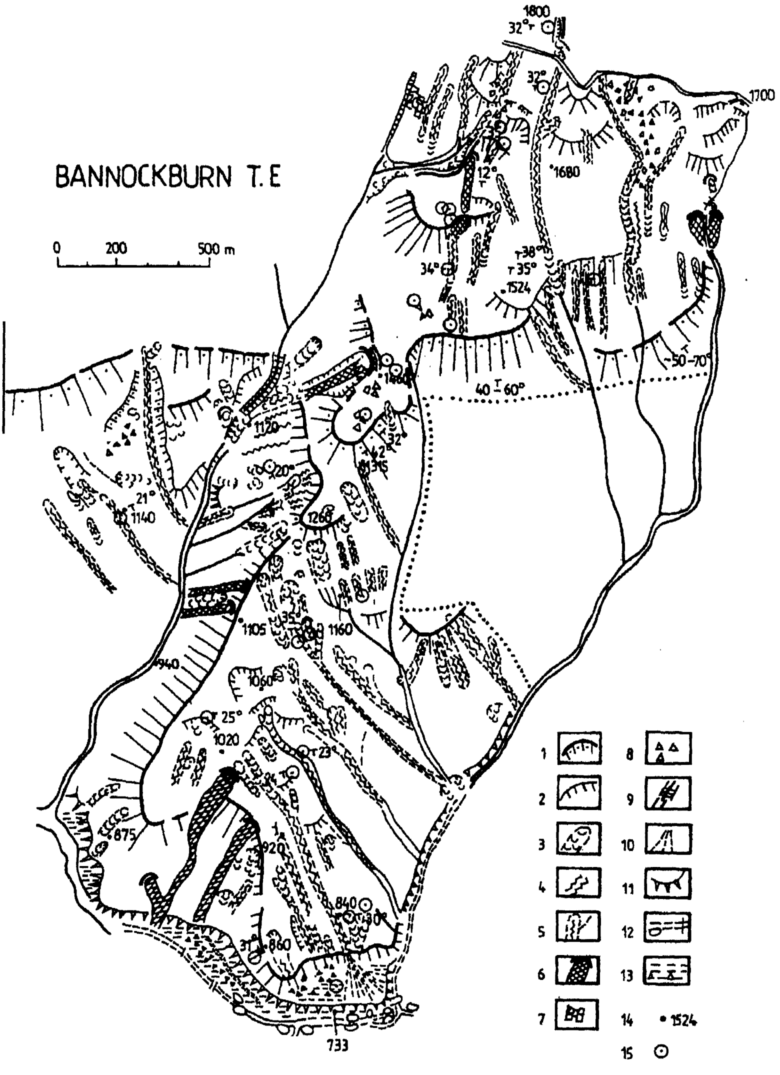
Morphography and Morphometry

The slopes of the Darjeeling Hills present a great diversity which is connected with young relief features and variations in geological structure[1,91]. Slopes are usually 1-2 km long and steep (20-48°), their difference in the altitude varies from several hundreds of meters to 1500 m. They are mainly rectilinear or convex (Fig. 3.7), but a more closer look may reveal less developed concavities inclined at 10-25° hanging above rocky undercutting (from 10-30 m to above 100 m high). Most of long slopes have step-like profiles. Steeper sections are controlled either by more resistant beds and have cuesta-like character or are created by large rockslides (or rockfalls). Gentle sections (5-25°) may represent less resistant rocks or fragments of older valley levels. In case of slope at Bannockburn TE 2600 m long, several structural scarps inclined at 40-60° and undercuts were recognised with gentle sections in between (Fig. 5.1). Therefore there exist local base levels which control different thickness of loose sediments and an independent modelling of slope sections. Steep sections are rocky. On gentle section the regolith may pass over 4 meters. The studies of the physical parameters of regolith controlling the mass movements are relatively rare. The plastic limit over the schists and gneisses fluctuate between 19 and 28%, the liquid limit 23-32% and the plasticity index 3-6%[96].

Slopes are also differentiated in transverse profiles. Flat slopes are relatively rare. These are either dissected by deeper gullies or landslides or by shallow depressions of former mudflow or debris flow tracks. The latter ones cause a much higher density of dissection reaching 2-5 km km^{-2}.

Slope Processes and Forms

The relief of slopes reflects a variety of slope forming processes. Among them various types of mass movements, slope wash, piping, linear erosion



1. Structure, controlled scarps, 2. Other edges, including old niches, 3. Post-landslides depressions (formed in 1968), 4. Slope fragment with degraded soil, 5. Debris flow channels formed in 1968, 6. New landslides and flows formed in 1987 (some of them in 1983), 7. Socky slopes, 8. Rocks (or big blocks), 9. Channels cut in bedrock (also with waterfalls), 10. Deluvial or colluvial fans, 11. Undercuts, 12. Channels cut in coarse debris with big blocks and waterfalls, 13. Fragments of terraces, 14. Elevation (in meters), 15. Sites where soil properties were measured

Fig. 5.1: Geomorphic map of part of the Bannockburn T.E. /by E.Gil and L.Starkel[91]

and the most common chemical denudation may be distinguished (Photo 8).

Among gravitational forms the rockfalls are restricted to steep undercuts along the rivers, where blocks of various size and larger weathered packets were dislodged. At several places in headwater areas steep niches connected with great rockfalls, combined probably with sliding or slumping of millions of cubic meters of material were found.

Deeper landslides also are relatively rare and are concentrated near undercuts or in headwaters. Several of them were created in 1968[1]. Slumps are small, but more frequent and follow the road undercuts. Among all types of mass movements the most common are earth flows and debri flows, active during extreme rainfalls. Earth flows form the tracks up to 1000 m long and 1 to 20 m wide over slopes inclined at 15-35°. Depending on the depth of weathered substratum these are 0.5 to 2 meters deep. The flows start mainly from the steeper inclines (slumps) and end either in the creek or form fans on the gentle flattenings. The debri flows are restricted either to steeper slopes, or to deep slope gullies cut in the bedrock. These flows incorporate blocks several meters in diameter.

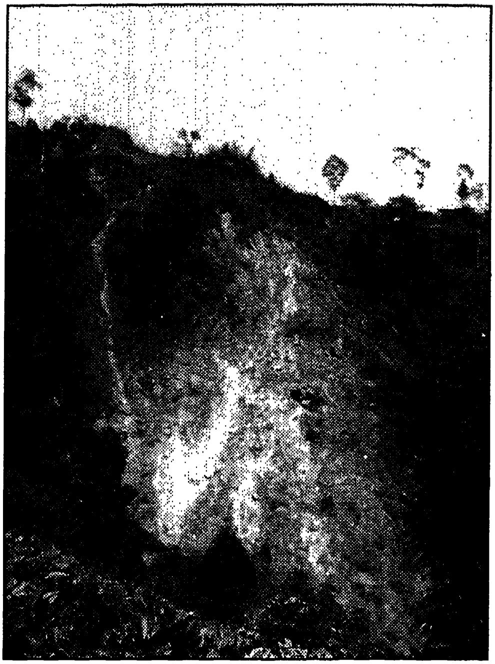


Photo 8: Rejuvenated landslip on steep scarp in Bannockburn T.E. On the left small channel carrying water from the village located upslope (1986) (by W. Froehlich)

Slope wash is rarely observed due to high permeability of soils. On the terraced slopes it causes replacement of soil. After rains there are frequent signs of piping. Their open channels are visible in the headparts of earthflows and in the niches of landslides.

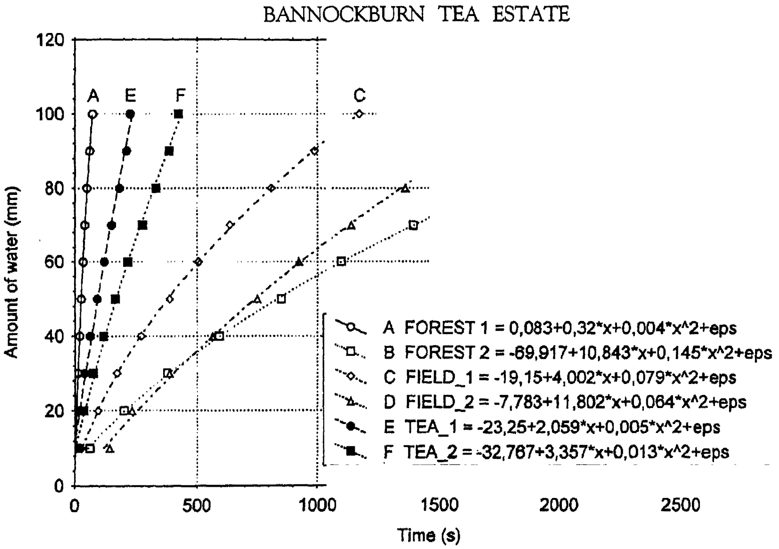
A most common process is chemical denudation, which causes leaching of various minerals from the regolith as well as the weathering of bedrock.

On deforested slopes during rainy season the saturated soil is characterised by soil creep, but more detail measurements of it are not available.

5.2 Runoff Generation

Rainfalls and its intensity as well as the existence of two contrasting seasons of monsoon are reflected in the water circulation on the slopes and in the flow regime. The transformation of precipitation into runoff is partly controlled by long steep slopes and physical properties of relatively permeable soils (cf. Chapter 3.2). A distinct vertical zonality of hydrological parameters is connected with rainfall and temperature gradient. The snowline in this part of Himalaya is elevated at about 4880 m a.s.l[96].

A characteristic feature of the Darjeeling Himalaya is a very high infiltration rate in the soils and jointed rocky substratum (Fig. 5.2). Even during extreme rainfalls the subsurface drainage prevails with



A, B–Forest; C,D–Terraced field; E,F–Tea plantation

Fig. 5.2: Infiltration rate of top soil depending on various land use

only slight overland flow[1,66]. Also from other parts of the Middle Himalaya the overland flow is reported as a very rare event[97-99]. but all these observations are not supported by the direct measurements in the field. Only in the east in the Meghalaya Plateau, K.D. Sharma and J.F. Correia[100] carried out the measurements of the overland flow and slope wash using Gerlach's troughs.

In the Darjeeling Himalaya region the prevailing high density of tea bushes on slopes counter not only the creation of overland flow but also rill or interrill erosion[1]. Also the narrow steps on the cultivated fields reduce the velocity of water and the downslope transfer of sediment. Thus, the cascade system of sediment delivery prevails there.

The measurements of water circulation on the slope were carried out in September 1987 and July 1988 during the summer monsoon and sporadically in the dry season of 1984, 1986 and 1989. Therefore we considered various characteristic seasons of the year excluding only the start of the rainy season.

In order to prove the substantial role of the accelerated subsurface runoff in flood generation[1], the measurements of threshold values of the overland flow and the infiltration rate on slope profiles and spring discharges were conducted in the tea gardens of Bannockburn, Ambootia and Pussimbing.

In Bannockburn TE the dispersed overland flow was measured using plastic bags of 150 liters capacity[101]. The yield of rocky springs supplying water to the pipe line was measured by volumetric method. The measurements of infiltration rate during several consecutive days in relation to varying soil humidity were carried out using the Burger's cylinder on the longitudinal slope profiles. These measurements were performed on the ground surface and at the depths of 5, 10, 20, 30, 40 and 50 cm. At each point the cylinder was poured over 3 to 5 times (each of 1000 cm^3 volume, what is equal to 100 mm of rainfall or 100 l m^{-2}). The infiltration rate of every 10 mm of water layer was registered. Over the landslide surface the infiltration was measured at the depth of 5-10, 20-25, 50-55, 100-105 cm and on several places at 2, 3 and 5 meter depth.

During the extreme rainfalls the subsurface drainage prevails with small pocket of dispersed overland flow[1,91]. At Bannockburn TE in July

1988 during a rain of 50 mm with an intensity upto 0.5 mm min^{-1} the overland flow between 1 and 61 m^{-1} was noticed at three spots (Fig. 5.3). Such dispersed overland flow may be created depending on local circumstances, rainfall features and soil humidity[97].

It may be assumed that rains of similar parameters pass the threshold of the overland flow[65]. But this is valid only for the slopes undisturbed by mass movements and covered by tea bushes, which restrict the length of overland flow to less than 1 m. Simultaneously on the sparsely vegetated surfaces between isolated tea bushes the overland flow was registered already during 25 mm rain and intensity 0.2 mm min^{-1} (Fig. 5.3). This value is probably much lower on the bare landslide surfaces. On the contrary the linear runoff in the slope gullies and along roads may be observed just after every rain[102].

The diversity of the grain size composition and structure of the regolith are controlling the differences in the permeability at various depths (Fig. 5.4). In the longitudinal slope profiles there exist sections of various conditions for water storage and rate of water transmission downslope. Such variations in the rate of surface drainage at various slope sections cause the rise in the pulsation of the seepage pressure, reducing the threshold values of slope stability[103].

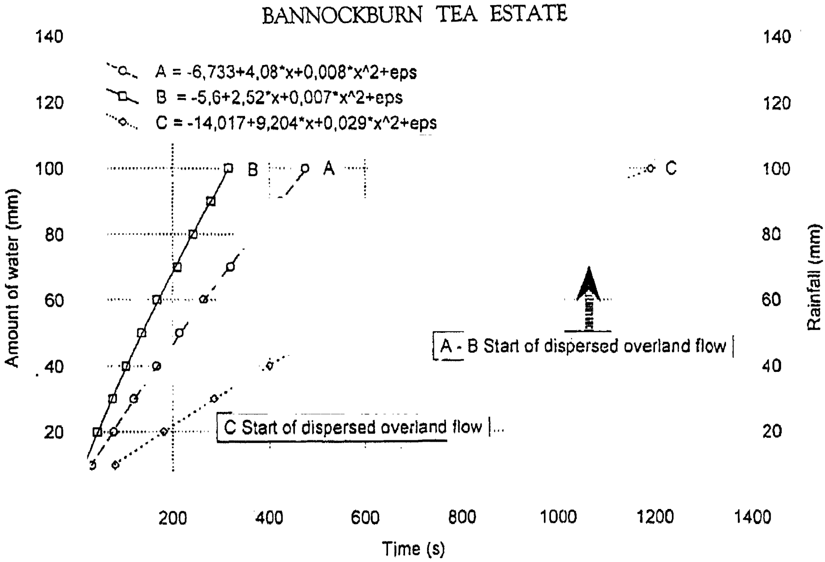
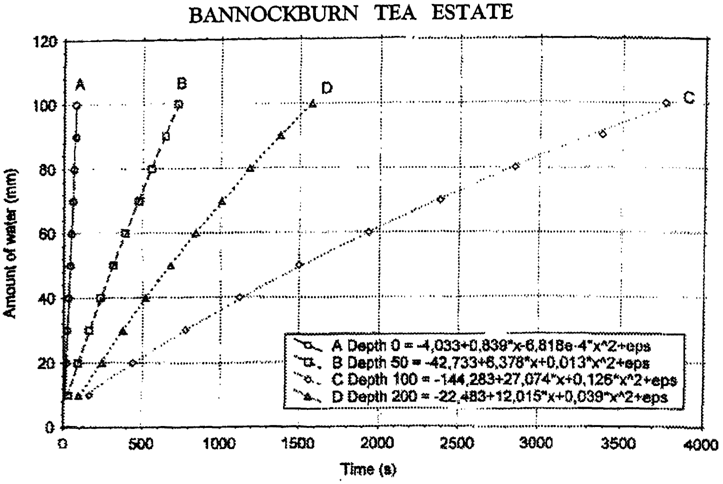


Fig. 5.3: Thresholds of rainfall generating the start of dispersed overland flow at Bannockburn T.E.



A-Topsoil, B-50 cm depth, C-100 cm, D-200 cm

Fig. 5.4: Changes of infiltration rate in soil column

The experimental measurements carried out in several tea gardens indicate that the soil profile (mantle) undisturbed by gravitational processes may absorb 100 mm of rainfall during 3-25 minutes (Fig. 5.5 and 5.6). Therefore it is highly realistic that during extreme rainfall with intensity exceeding 1 mm min^{-1} as in October 1968 water might be totally absorbed by the ground[1].

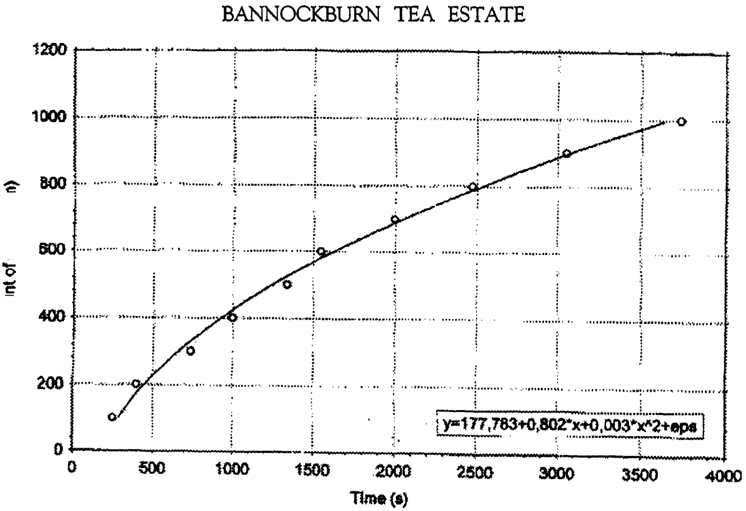


Fig. 5.5: Experimental infiltration measurements of topsoil after 1000 mm rainfall

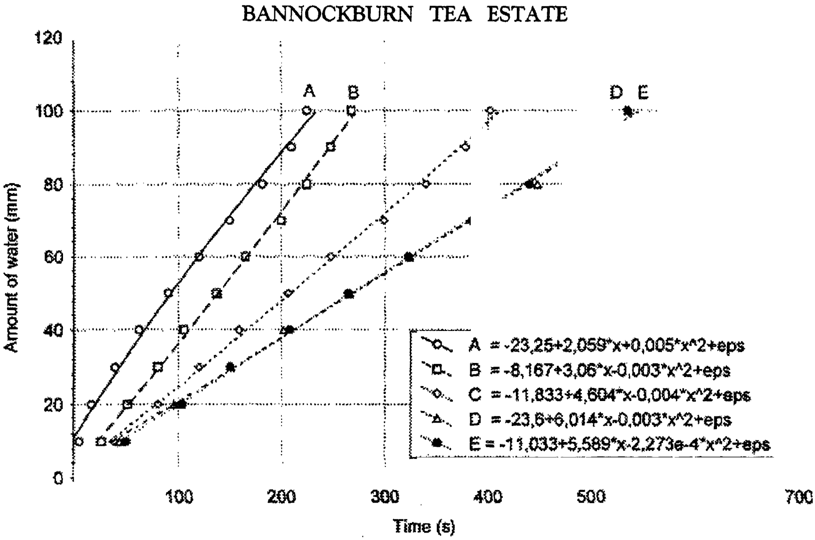


Fig. 5.6: Differentiation of infiltration rate of topsoil surface of 100 mm rain established during successive (A-E) pouring of Burger's cylinder

Much greater diversity in infiltration rate was recorded on the slopes disturbed by mass movements, where superimposed colluvial layers of various physical properties exist (Fig. 5.7). At Bannockburn TE over the landslide tongue at 25 cm depth the permeability was lower by 38% in relation to the ground surface. At 50 cm depth it declined even to 12% and increased again to 48% at 1 m depth. Very distinct changes in the permeability were measured in the thick colluvia, when due to the compaction at 2-5 m depth the infiltration decreased to 30% of the ground surface value. The rates and directions of the subsurface transmission of water downslope were measured by use of luminophore (fluorosceine and fucsine). The experiment was made on the slope surface above the niches of the great Ambootia landslide valley during the beginning of dry season in October 1989[64,65]. The flow-outs were observed in the scarps of Ambootia landslide and the rate of subsurface water transmission in the debris deposits was calculated to 5-12 m h^{-1}. During extreme rainfalls it may be much higher, because the infiltration follows over the whole slope surface, the ground is fully saturated and the saturated overland flow and delayed return flow are created (Fig.5.8) This transmission may be accelerated by deeply inclined jointed bedrock and by increasing seepage pressure downslope, especially closely to the unweathered

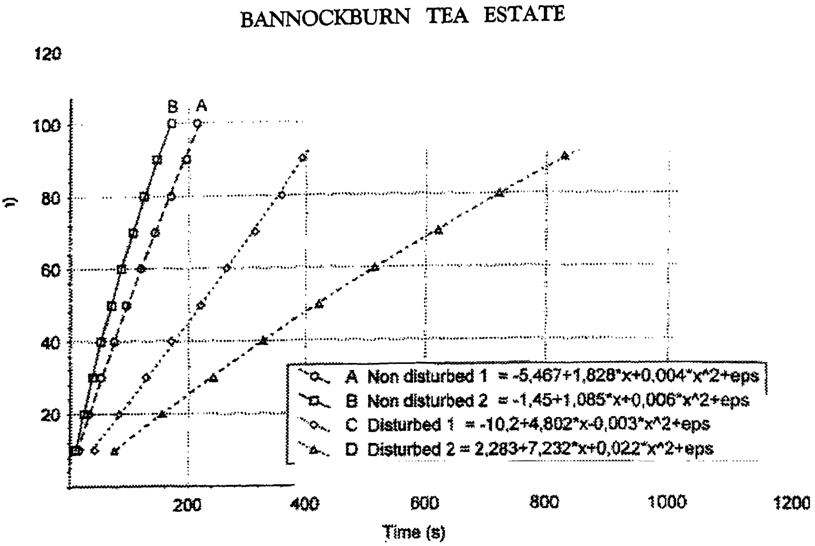


Fig. 5.7: Infiltration rate on slopes non disturbed (A,B) and disturbed (C,D) by mass movements

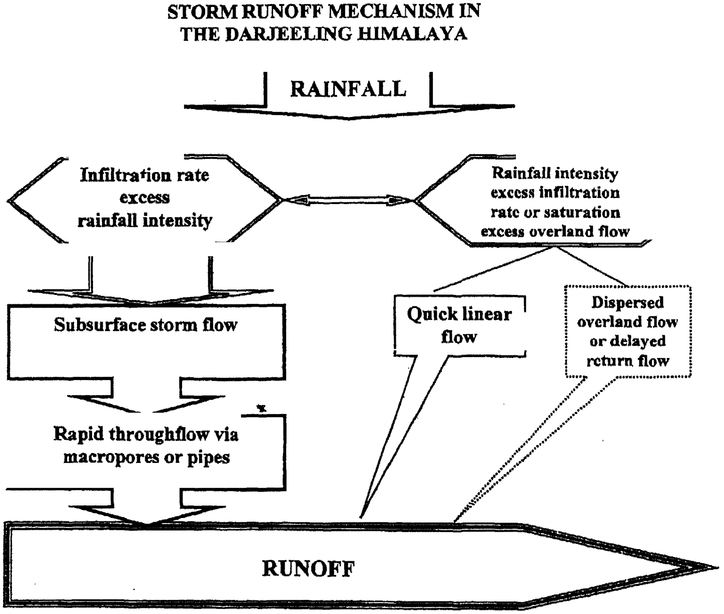

STORM RUNOFF MECHANISM IN THE DARJEELING HIMALAYA
RAINFALL
Infiltration rate excess rainfall intensity
Rainfall intensity excess infiltration rate or saturation excess overland flow
Subsurface storm flow
Quick linear flow
Dispersed overland flow or delayed return flow
Rapid throughflow via macropores or pipes
RUNOFF

Fig. 5.8: The model of runoff mechanism during extreme rainfalls in the Darjeeling Himalaya

bedrock surface. A great diversity of physical and textural properties of substratum decides on the various role of water circulation especially of piping type.

On the contrary several repeated measurements of rocky springs show that these have stable discharge. Even during dry season their discharge regression is very slow, suggesting the existence of deep efficiency of groundwater reservoirs, controlling the maintenance of river discharge during dry season. The most efficient are the headwater areas deeply incised in the bedrock with the preserved patches of jungle. Nevertheless steep gradients of slope surface and bedrock, coarse regoliths accelerate the runoff. This is reflected in a rapid runoff generation during heavy rains and registered in steep rises of water level on hydrograms. The mechanism of this response has been well documented in the small catchment (12.85 km^2) of Peshok Jhora, right-side tributary of the Tista river (Patel and Soja,[104] Chapter 6.2 and Fig. 5.8).

5.3 Mass Movements Created During Extreme Rainfalls

The Continuous Rain in October 1968

Till the end of September 1968 rainfall in Darjeeling town was recorded to be 2044 mm. Then there was a 4-day break, and on 2nd October, when the rain started again, the surface layer of soil had already been dried out, being capable of absorbing large amounts of water. During the next 52 hours rainfall was recorded between 600 and 1100 mm (Fig. 4.6 and 4.7) and due to high infiltration rate lot of water percolated to the ground. The rain intensity of 10-20 mm h^{-1} filled the capacity of the waste covers and water began to percolate under the influence of seepage pressure. The lack of rills on the ground surface (rills were observed on one slope only), indicated that only sub-surface run-off took place. Some water could flow on the bare rocky slope fragments, as well as infiltrate deeper along joints into weathered gneisses. When after about 45 hours the rainfall intensity increased further and reached 1 mm min^{-1}, the water infiltrating into the soil being unable to store anymore and began under pressure to form piping channels in the regolith, gushing out in the form of springs and the soils reached the threshold of liquifaction. A small portion of the water penetrating deeper give rise to episodic springs and facilitated the formation of large and deep landslide valleys (cf. Ambootia landslide valley).

Therefore the main features formed during this rain were the immense earthflows and debri flows (Photo 9,10). This water with debris flowing

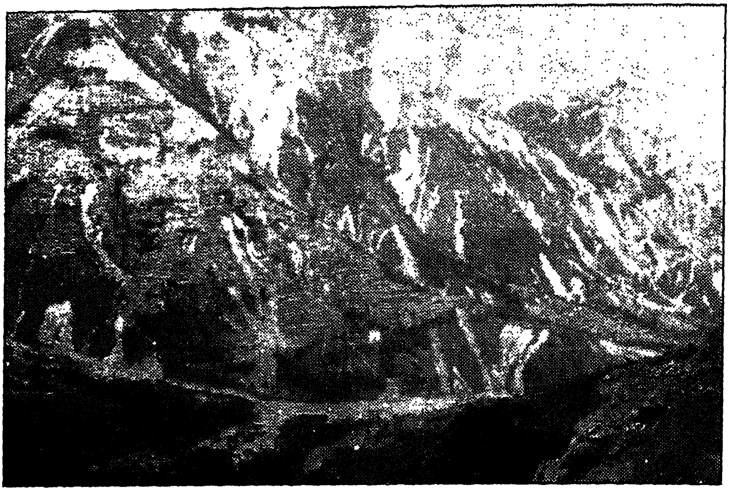


Photo 9: The left deforested slope of the Little Rangit valley dissected by hundreds of debris- and earth-flows after continuous rain in October 1968 (December 1968) (by L. Starkel)

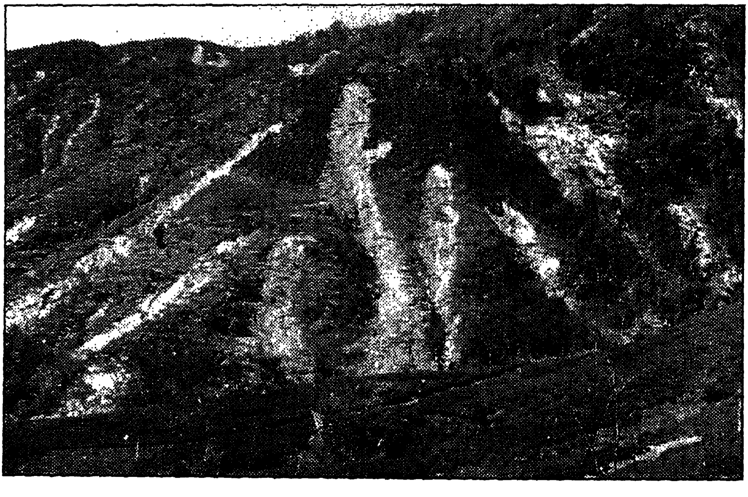


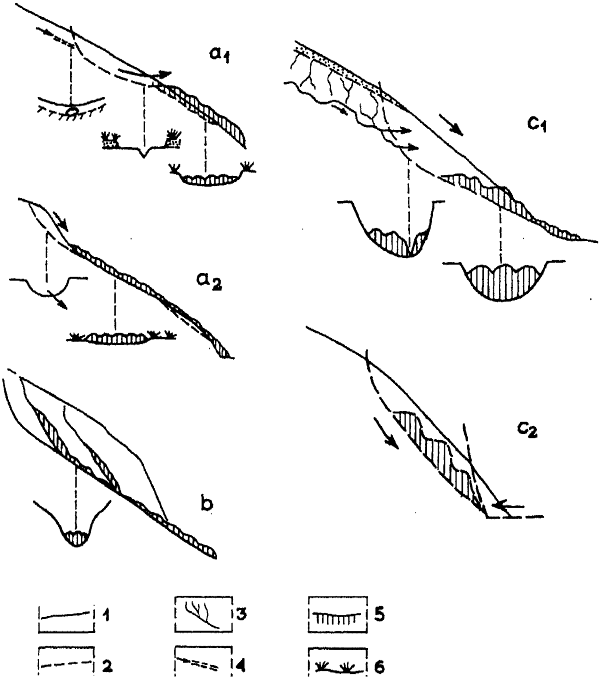
Photo 10: Parallel debris- and earth-flow tracks in Ringtong T.E. formed in October 1968 (December 1968) (by L. Starkel)

downslope concentrated in small creeks forming flood waves of 2-5 meter in height.

Among mass movements the following types were distinguished[1]:

I The most common were mudflows (or earthflows) and mixed debris flows, being of two kinds (Fig. 5.9):

i) The first sub-type, most frequent in tea gardens, started on slopes of 25-40° inclination, after a considerable distance from the watershed, mainly in shallow slope depression, in which percolating water was concentrated. These flows started with a steep oval niches 1-2 m high (depending on the thickness of the regolith)



a_1-Mudflows connected with piping (sufosional channels), a_2-Slumps-mudflows b-Debris flows directed by slope gullies, c_1-Debris - rocks slides connected with deep percolation, c_2-Landslides and slumps created by lateral erosion.

1. Slope surface before movement, 2. New erosional profile, 3. Joints conducting ground waters, 4. Sufosional channel, 5. Flowing or sliding material, 6. Soil covered with tea bushes

Fig. 5.9: Types of mass movements during heavy rain October 1968 (after Starkel[1])

with outlets in the piping channels. Their continuation were long channels with depths corresponding to the depths of root system of tea bushes (Photo 10). Such channels had steep margins and were from several to 40 m wide, being often cut by a furrow of 0.5-2 m deep exposing the unweathered rock. Such channels may be the remains of the piping canals. The mass flowing downslope spread over flattening (10-20°) overcoming steeper fragments. The winding course and preserved trees on its way indicated that it was a liquified mass (Photo 11). Several flows were upto 1000 m

Photo 11: Fragment of earth-flow mass in Bannockburn T.E. (December 1968) (by L. Starkel)

Photo 12: Colluvial fans deposited on the higher terrace of the Rangnu creek, Bannockburn T.E. (December 1968) (by L. Starkel)

long and ultimately reached the river channels or formed the proluvial fans inclined at 10-15° (Fig. 5.1 and Photo 12).

Inclination of 15-20° of such stabilised tongues correspond to the angle of internal friction of saturated sandy loams. At Chongtong spur with thick clayey soils the liquifaction occurred at lower gradients. Some flow tongues had been held by tea bushes or groups of trees on slope shelves. In such cases the water released from mudflows deposited in the forest and on the plantation beneath washed out the top soil layer of 0.5-1.0 m thickness (at Bannockburn TE).

ii) The second subtype is represented by debris flows and mudflows which started from small slumps on the steep slopes either on structure controlled edges or on undercuts of roads and edges of field terraces inclined at 35-50° and more. The saturated mass slumped down pushing the saturated soil, later transformed into flow tongue. Sometime the edge zone was supplied with water percolating from the slope above. Several flows started in the deforested fragments of the jungle and their muddy tongues stopped spreading among the trees and bushes.

II The debris flows directed by gullies inclined at 40-60° which existed before this event. These gullies collected masses of small and bigger flows and slumps created in the upper parts of slopes as well the running water (Photo 9,13). The passing of angles of friction afforded possibilities of higher velocities of these masses and transportation of large blocks several meters in diameter.

III Deep and large rockslides were formed either in places

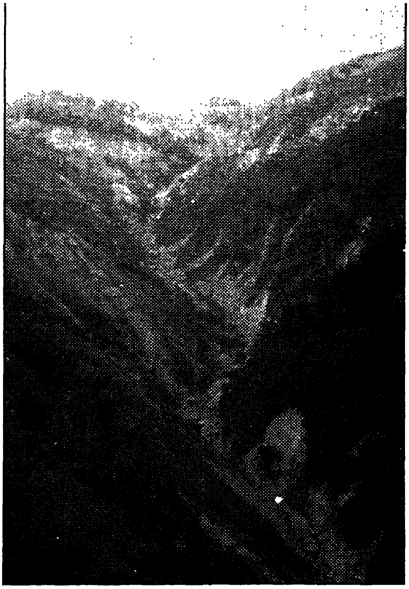
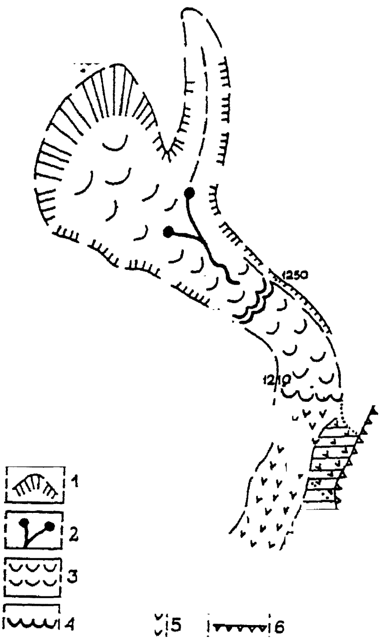


Photo 13: Debris flows in the headwater area Poobong T.E. (December 1968) (by L. Starkel)

of deep percolation of water or at undercutting slopes by flood waters.

i) Deep infiltration in joined bedrock caused the formation of large rock slides on slopes inclined at 25-35°, sometime up to 0.5-1.0 km and more in length (Ambootia - Froehlich *et al.*, 1992). Several landslides were formed near Poobong (Fig. 5.10). These landslides were composed of 2 parts: upper one rocky with steep niche and lower tongue of liquified earth mass partly superimposed on valley bottom. The masses of these



1. Niches and scarps, 2. Springs and erosional furrows dissecting the sliding blocks, 3. Sliding mass, 4. Forehead of sliding mass, 5. Earthflow, 6. Lateral erosion of Posam creek, 7. Terrace, 8. m high, partly covered by debris flow

Fig. 5.10: Geomorphological sketch of a big landslide in Poobong T. E. about 350 m long. Upper part – rock slide, in the lower earthflow (after Starkel[1])

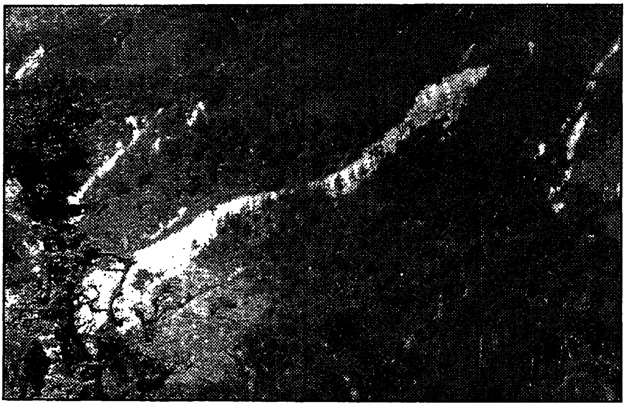


Photo 14: Large rocky landslide in the jungle in the headwaters of the Balasan river formed in October 1968 (December 1968) (by L. Starkel)

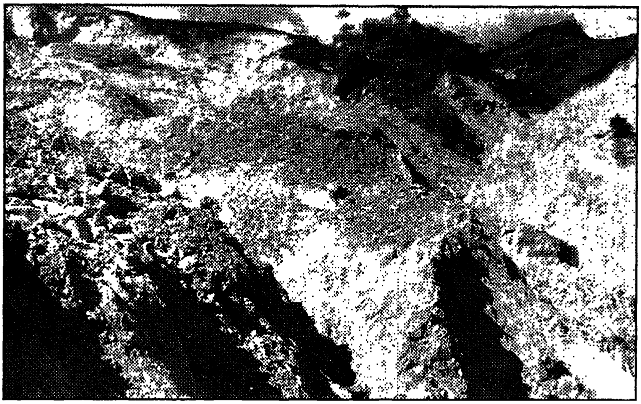


Photo 15: Upper part of rocky landslide at Poobong T. E. (December 1968) (by L. Starkel)

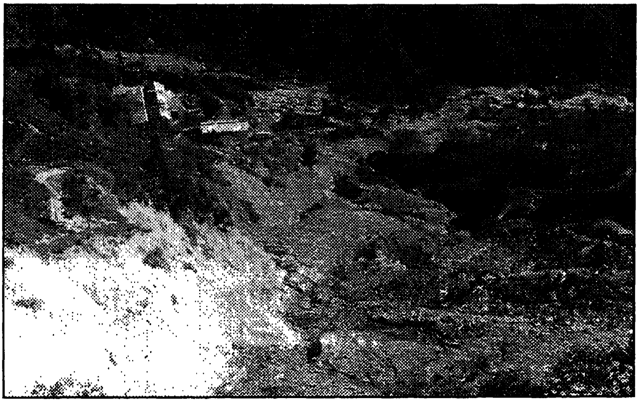
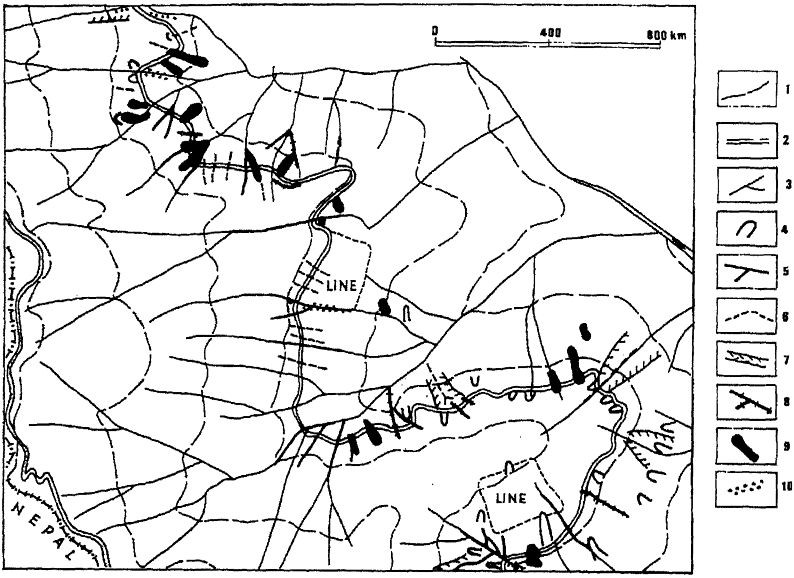


Photo 16: Lower part of rocky landslide at Poobong T. E., reaching the Posam creek with extensive debris flow. On the left isolated tea factory (December 1968) (by L. Starkel)

landslides were frequently incorporated in the debris flow moving along the main river channel (Photo 14-16).

ii) The valley sides of the Tista and tributaries were undermined during this flood. On these slopes were formed big rock and earth slides, especially in the parts built by the less resistant Daling shales or by thick covers of waste material. The niches are visible near Tista Bazar or near Pul-Bazar. Most of the tongues were later carried away by the flood waters (Photo 48).

The differentiation in the type and intensity of processes depended on various local factors. Among them shallow infiltration of water, causing liquifaction of soils was mainly important. On the Daling shales larger number of flows were noted. The role of plant cover was also significant. On the terrains of tea gardens the range of areas affected by mass-movements fluctuated from 10-26 percent[1], on terraced fields it reached even 30-50 per cent. At elevations of 1500-2500 m a.s.l. with high percentage of forests the mass movements occupied 10-20 times less area than on the tea gardens. Observations in the forested headwater of the Little Rangit valley (Fig. 5.11) showed that landslips and slumps, as well as several furrows were concentrated along the roads. In the forested valleys at least 60% were inactive, some underwent dissection (rejuvenation) and in several the fresh transportation or accumulation of gravels was recorded. On the contrary, considerable changes were observed along main roads in deforested areas. The Hill Cart Road connecting Siliguri with Darjeeling was affected by flows, slumps and slides at about 200 sites.



1. Contour lines each 500 feet, 2. Roads, 3. Creek, 4. Slips and flows formed in 1950 (mapped by forest officers - cf. Ninth Working Plan[105A]), 5. V-shaped valleys, inactive in Oct. 16, 68, 6. Inactive gullies, 7. Breaks and scarps, 8. New gullies, 9. Channels of earthflows, 10. Landslides, 11. Boulders accumulated in valley bottoms

Fig. 5.11: Example of mapping of forest areas in Little Rangit Block. New changes after October 1968 underlined

Some regional differentiation in density of flows and slides appeared between areas of various rainfall totals. In Ringtong TE where only 602 mm of rainfall was recorded the damages on slopes were 2-3 times lower than at Poobong TE located in headwater area where 765 mm of rainfall was recorded.

Assuming that 20 per cent of deforested slopes was affected by mass movements during rainfall in October 1968, the mean thickness of displaced layer reached about 20 cm on the average[1] whereas in the forested areas the mean degradation never exceeded 1 cm.

Other Extreme Events Recorded in the Darjeeling Hills

In the last century the two other continuous heavy rains of similar extension and totals to that of October 1968 (cf. Chapter 4) were recorded.

In 1899 in two days (24-25 September) 691 mm of rainfall was recorded at Happy Valley TE. K.K. Dutta[48] and A.J. Dash[93] also reported numerous landslides.

In June 1950, the continuous rain lasting for 4-5 days was distributed unevenly over space (278-1500 mm, Fig. 5.12). The greatest damages were reported from the Darjeeling town, where many slopes with houses descended at that time[46-48]. S. Ray and S.B. Sen Sharma[105] distinguished three types of mass movements: debris-slides, rock-slides and soil creeps (Photo 17). K.K. Dutta[48] describes large flows in the

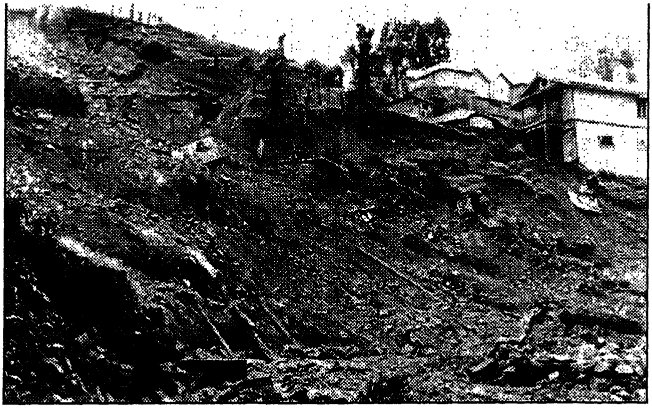
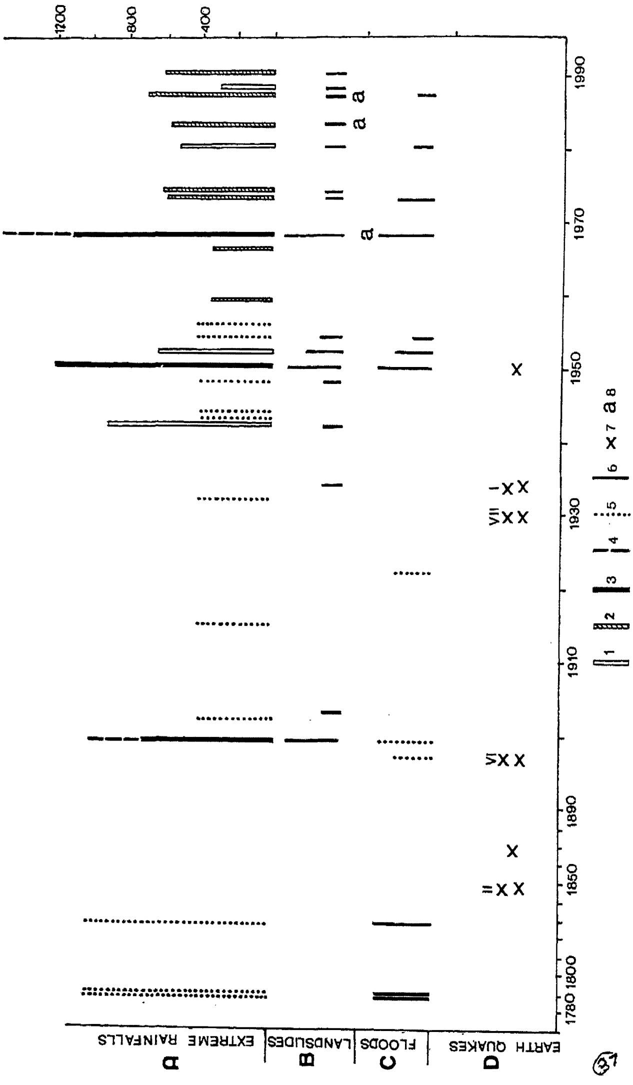


Photo 17: Landslides in Darjeeling Town in June 1950
(made by Das Studio, Darjeeling)

tea gardens upto 30 meters wide. Also many landslides were recorded in the forested areas (Working Plan 1955). A big slide was formed near Sonada, later reactivated in 1968.

Similar but less extensive rain was recorded in 1952 when on 22nd September Kurseong noted 624.4 mm and near Lebong a large landslide was formed[51]. Various sources mentioned new landslides occurring in 1903, 1934 and 1954.



1. Heavy downpours, 2. Continuous rain (local), 3. Continuous rain (regional), 4. Continuous rain (higher totals outside Darjeeling), 5. Notes about heavy rainfalls or floods, 6. Flood deposits or landslides, 7. Earthquakes, 8. Ambootia landslide active

Fig. 5.12: Extreme events registered in last two centuries (extreme rainfalls, landslides, floods, earthquakes)

During our studies starting from 1984 several events of more local character than in 1968 were recorded, reflecting the formation or reactivation of landslides (Fig. 5.12).

In August-September 1980 several landslides and debris flows were recorded after rains exceeding locally 350-500 mm. Similar rains in June 1983 in Bannockburn caused formation of landslides on the edges of steep valley sides. Several similar slips and rejuvenation of the older ones were registered in Bannockburn TE and Ambootia in 1987. Heavy downpour on 17th July 1988 near Kurseong created many slumps and debris flows in the gullies undercut by road construction. Also in the 80's at Sonada and Ghoom dozens of mudflows and debris-flows similar to created in 1968 were observed, but this time restricted to small areas of 1-3 km^2. Heavy rains in Ranglie-Rangliot TE in 1990 caused sliding and formation of gullies.

5.4 Landslides and Water Management in Darjeeling Town

Landsliding is perhaps the most rampant environmental hazard threatening the Darjeeling town itself. Numerous slips have occurred in the past; however the intensity, cause and severity of the slides are being recorded only since 1899. From the records of the recent landslide events, it is quite clearly revealed that the frequency of landslips is increasing from decade to decade. In order to have an insight into the probable causes of such increased vulnerability of the Darjeeling town it is necessary to trace the course of events from the very inception of the town and its impact on drinking water supply[106].

Geomorphological and Geological Background

Darjeeling is situated at the northern extremity of a ridge, which extends southwards through Ghoom and is bifurcated by numerous spurs. The main ridge and the spurs are flattened but narrow and with steep slopes and are separated by water channels of steep gradient locally known as Kholas and Jhoras.

Within the confines of Darjeeling town the foliation dips of the gneissic rocks are generally towards the east, ranging from 20 to 40°. There are two prominent sets of joints, one running roughly NW to SE and the other NNW to SSE. Both the joints have steep westerly dips varying from 40-70°. The general direction of the hill spurs agreeing with the joint directions indicate that blocks of rocks loosen easily along these joints.

In Darjeeling town, only near the crest of the ridges, there is topsoil of about 3 to 5m, but the thickness decreases downwards and lower slopes are generally covered with boulders rolled down from the top. The soil everywhere is residual as it is derived from the weathering of gneissic rocks. Weathering is selective in these rocks and proceeds along some susceptible bands - mica rich bands in preference to quartzose bands and also along joints and shear planes. As a result, blocks of fresh rocks are generally found encircled on all sides by highly weathered rocks. The clay is found mixed up with grains of quartz, feldspar and flakes of mica. This has got an important bearing on the slips, as the air filling up the voids in clayey soil gives it an apparent cohesion, which is lost as soon as the pores get filled with water during rains.

The reason for formation of the soil-covered (1.5 to 3 m) western slope contrasting with the boulder-covered eastern slope is probably to be attributed to the characteristic structural features of the underlying rocks (joints, foliation dip etc.) in the respective area. On the eastern slope, foliation plane and joints are favourable for loosening of blocks to form talus while on the western slope, the foliation dip being inward, the loosingly of block is retarded and the rocks get time to weather into soil.

Development of Darjeeling Town

In 1835 the population consisted only of a few hundreds of people. With the establishment of a sanatorium for ailing British soldiers,

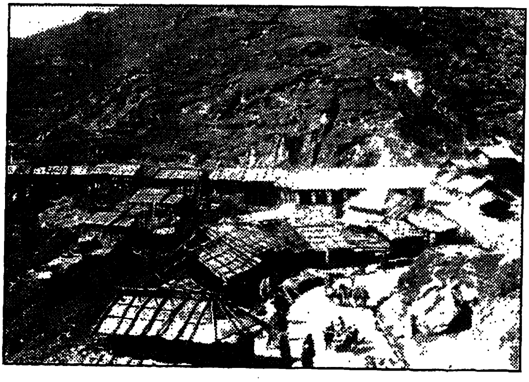
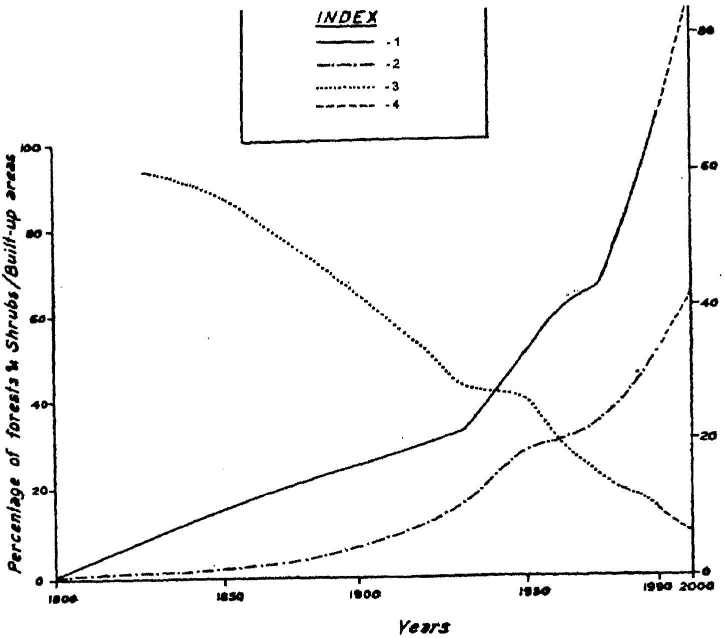


Photo 18: Primary settlement in Ghoom (2250 m a.s.l.). Extensive deforested slopes with active sliding and creeping. Photo made in 1870-ties or 1880-ties, probably before final construction of railway to Darjeeling (purchased at Das Studio, Darjeeling)

purchase of land by Europeans for residential purposes, opening up of barracks for soldiers and a Bazar (market), population grew upto 10,000 in 1850. When the tea gardens were being open out and the Hill Cart Road and Darjeeling Himalayan Railway line were constructed (Photo 18), labourers poured in and a phenomenal growth of population (16924 persons) resulted in 1901.

Success of tea plantation, partition of Bengal, introduction of tourism and the resultant massive construction works (expansion of roads, construction of new urban structures etc.) ushered in more and more immigrants from the neighbouring countries and thereby almost doubling the population of Darjeeling (33,605 persons) in 1951 and by 1991, the town recorded a population of about 71,471 persons, the density figure changed from 1603 persons km^2 in 1901 to 6769 persons km^2 in 1991 with a consequent change in percentage of increase of 322 (Fig. 5.13 and Table III).



1. Population, 2. Built-up areas, 3. Forest and shrubs, 4. Projected

Fig. 5.13: Decline of forest areas and rise of population and urban areas in Darjeeling municipality

Table III: Decrease in forest and increase in built-up areas and population in Darjeeling Town (1800-1900)

Year	Forest (%)	Built-up area (%)	Population
1800	95	0.0	100
1850	87	3.0	10000
1901	65	7.5	16924
1951	40	39.0	33605
1991	15	52.0	71479
2001*	10	65.0	85000

Projected

Source: Census Reports, Forest Census[156] and other documents

Upto the first half of the present century, there were certain regulations for the commercialisation of the hill slopes, but since independence (1947) in a desperate attempt to acquire as much arable land as possible, extensive area under forest cover were being gradually encroached upon. The ever increasing number of people haphazardly settled in every bit of land available. During the British period it was made a rule that forest on the upper parts of the hills should not to brought under ordinary commercial forest management. They had the notion of the ecological disaster that it would bring out if these forests were denuded. But after independence the demand for timber increased at an unprecedented rate, and even the upper layer of the forest was not spared[107]. Even after mass afforestation programmes have been implemented a big gap remains between felling and re-planing. It has been estimated that 70% of the cooking energy needs of the people is still being met by firewood. Needless and reckless obliteration of forests along with unscientific use of slopes (specially in construction works), coupled with geological, rainfall and slope characteristics have changed the local scenario completely. As a result Darjeeling, one of the most densely populated tourist-centres in a comparable environment, reaches just on the verge of an environmental catastrophy as with just one concentrated shower of 50 mm h^{-1} would initiate numerous landslides

Landslide Events

The map of all surveyed landslides (Fig. 5.14) has been prepared on the base of various sources[46,48,87,106,108]. From the available records, it is found that the first disastrous landslip occurred on the 24 September 1899, in Darjeeling town (Fig. 5.12). Unprecedented rainfall of 1065.5 mm during 23 to 25 September (3 days) triggered about fifteen

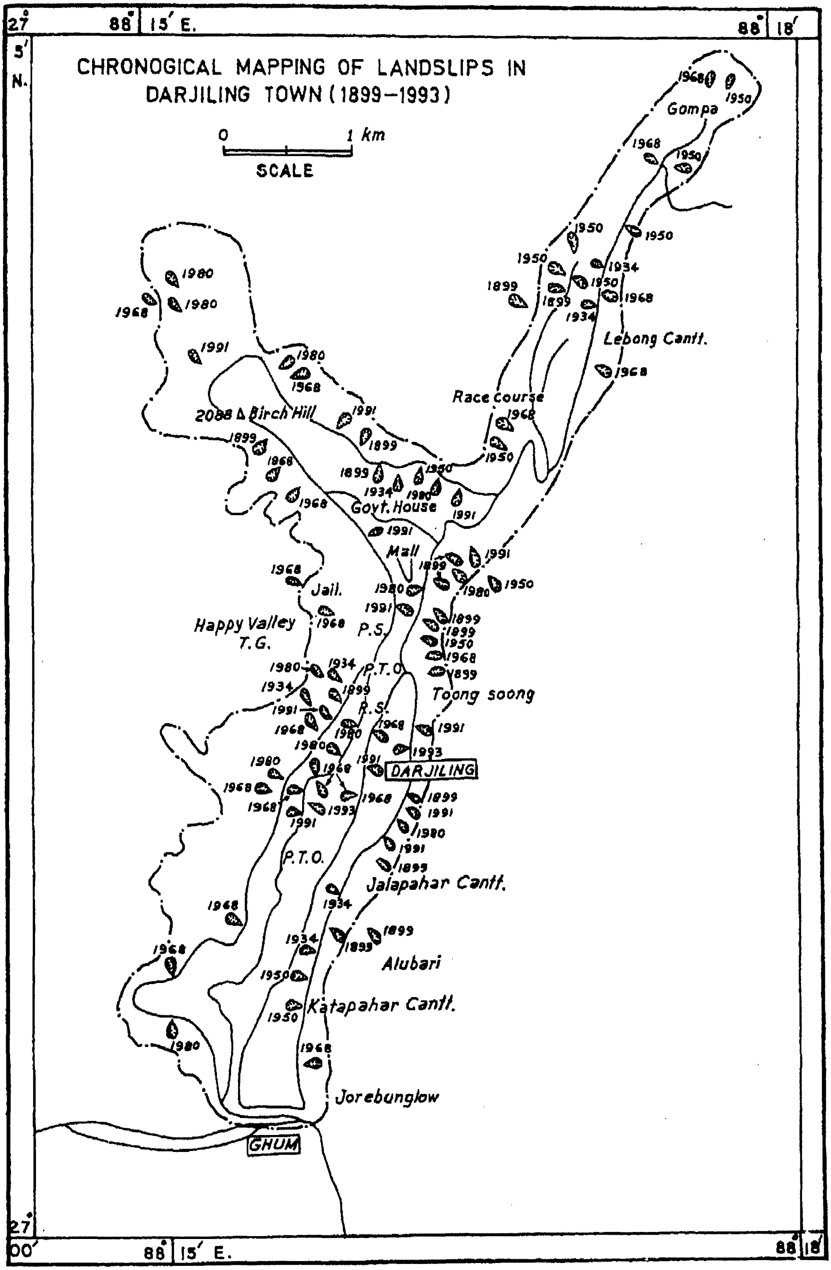


Fig. 5.14: *Map of landslides formed during various years in Darjeeling Town (compiled after various sources by S. Lama[87])*

landslides in different parts of Darjeeling town killing 72 persons and causing enormous loss to land and properties[44]. Most of these slips were confined to the soil cap overlying the gneissic rocks. The instability of the hillside gradually increased due to increased saturation caused by absorption of moisture. The artificial cutting of hill-slopes increased this instability further. Defective drainage was also considered an important factor.

The second major event of landslips in the town took place on the 15 January, 1934 due to Bihar-Nepal earthquake, which was responsible for widespread destruction though not of equal magnitude as was experienced in 1899.

On the 11 and 12 June, 1950, the hill slopes in and around Darjeeling town were affected by another disastrous event causing several deaths and heavy damage to roads, houses and public works, due to heavy continuous rain (834.1 mm) (Fig.5.12 and 5.14, Photo 17).

Darjeeling town and its environs were again eclipsed with large-scale landslides owing mainly to rainfall that continued from 2 to 5 October 1968 (see Chapter 5.3). Such landslides caused widespread damage and cut off the town from the rest of country for about a week.

The period between 1969 to 1979 was relatively stable. But heavy and continuous rain on the 27 August and again during 3 to 4 September 1980 triggered off widespread landslips. Since 1980, it has been observed that almost in every monsoon some part or other of the town has been suffering from major or minor landslips. The years 1991 and 1993 are the latest cases of landslips in Darjeeling town.

Landslide Prone Areas

For a better understanding of the geographical distribution of landslip-prone areas in Darjeeling town a map (Fig. 5.15) has been produced with the help of a 'checklist', topographical sheets (78 A/4 and 78 A/8) and direct field observations at 35 sample sites. The following 5 categories of susceptibility zone have been distinguished[87,108]. In this context it is interesting to note that the study of soil erosion also shows a more-or-less similar diversity.

Class I: Extremely high slip-prone zone. Almost after every torrential rain, these tracts experience slips. They are mostly found on the eastern

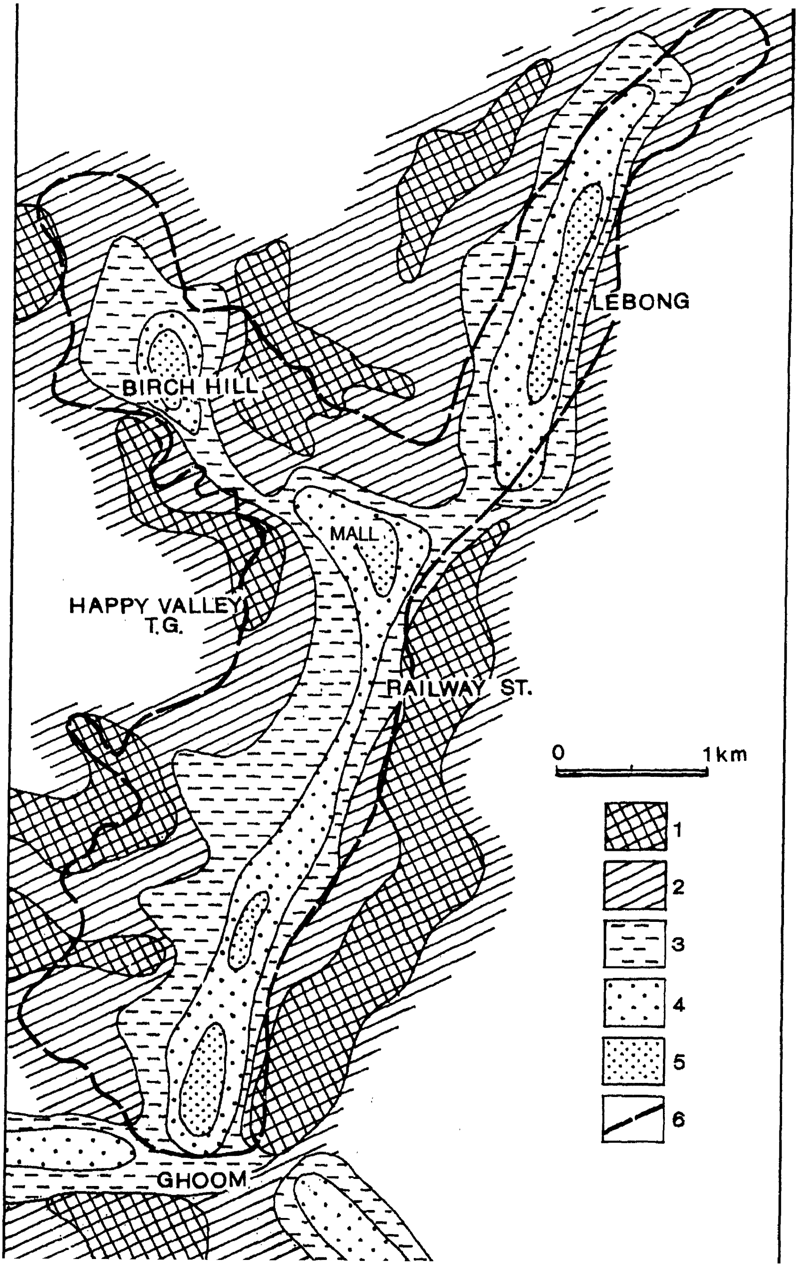


Fig. 5.15: Landslip-prone areas in the Darjeeling town (after S. Lama[87]).
Classes 1-5 – explained in text

slopes of Jalapahar-Katapahar ridge, eastern slope of Lebong spur, around Ging and Bannockburn tea gardens and in small pockets on western slope of the Lebong spur.

Class II: Very high slip-prone zone. These are the areas where slips occur for more than five times in ten years. They are found along both the eastern and western slopes of the ridge. It is also to be found on both sides of the Lebong spur mainly in the tea gardens.

Class III: High slip-prone zone. It covers the western spur of town along the Birch Hill spur and the Lebong spur. Here landslips occur 2-5 times in ten years.

Class IV: Moderate to low slip-prone zone. In this zone landslips occur once or twice in last ten years. It is found mostly along the ridges of Jalapahar-Katapahar upto the Mall, including the Bazar area and also along the Lebong spur.

Class V: None to negligible. It is restricted to the ridge tops of the Jalapahar-Katapahar ridge, the Lebong ridge (Military Cantonments) and the Observatory Hill and Birch Hill.

Water Management in Darjeeling Town

Slope instability has a direct relation to water supply in Darjeeling town. At present, the town almost wholly depends on the supply of 218 000 m^3 of drinking water from the following three lakes on Senchal ridge:

South Lake -	59,000 m^3	- opened in 1910
North Lake -	91,000 m^3	- opened in 1932
Sindhap Lake -	68,000 m^3	- opened in 1978
Total -	218,000 m^3	

Taking the UN standard of 90 l per head per day, the total demand for Darjeeling town has been estimated by the Municipal authority as 500 000 m^3 million (Darjeeling Municipal Report 1991). Considering the present population of 71,479 (1991) this demand will be much more pointing to a perpetual crisis in water in Darjeeling town. There would not be any water crisis if the storage capacity could be enhanced by the construction of at least 5 more reservoirs of the capacity of 45000 m^3 each. But the Senchal ridge is hardly stable enough to stand such construction of reservoirs. At the most one more reservoir can be constructed. So at present during monsoons only 8 out of 26 Jhoras feeding the Senchal lakes are kept alive, the rest are cut off, for there is no capacity to store[109]. The Rockville reservoir at the centre of the town above the railway station was affected by landslip in 1950 and it was feared that the reservoir also might be damaged and its bursting might cause further damage. The area that slipped, involved only the superficial layer of sandy clay and boulders originally resting at an angle of 40°, which is greater than the angle of repose for such materials. Lubrication further lowered the angle of repose and caused the slip[46]. Nearly 1000 m length of the top most water pipe-line located on the eastern slope of Darjeeling-Jalaphar ridge was damaged during 1950 monsoon. Slips had damaged and twisted the pipes at various places, causing temporary stoppage to water supply. The damages to pipes can be prevented by burying them underground. However, some protective measures should be provided to the pipe-lines in order to protect them against the impact of falling materials[48]. In 1988 and 1993, landslides damaged water pipe-line in different parts of Darjeeling also.

Depletion of forests and the increase in average run-off has helped in drying up of many local springs, which used to supply water to local people. The situation has deteriorated further in recent years. Villagers have to walk a few km in search of water during non-monsoon months and even the tourists living in moderate hotels have to pay Rs. 5-10 for a bucket of water during peak tourist season.

Recommendations

The study of individual slips within the town (Fig. 5.14) and identification of landslip-prone areas (Fig. 5.15) indicate that there is no portion, excepting only the very top of the ridges, which is stable against slips. However, the western slopes of the ridges and spurs are comparatively more stable than the eastern slopes. In the western slopes the debris cover is fairly thick below the present town limit, i.e., below the Cart Road and Victoria Road where the gradient is also steeper. So construction of buildings on the debris covered slopes should be restricted. In soil covered slopes building may be constructed but they should be provided with proper revetment walls with adequate weep-holes.

Narrow drains extending only a few meters down the hillside are found to have helped in the seepage into the hill-slope below causing slips. Cemented drains wide enough to drain out the storm discharges, should be constructed from the top to below, the lower level of the town.

In the busty areas (slums), the greater incidence of slips is mainly due to bad drainage from the densely packed houses, which in the absence of proper outlets gets absorbed in the soil. Unscientific and badly managed terrace cultivation adjoining the houses aggravates soil erosion. Low, badly designed and poorly constructed revetment walls also assist the slip instead of providing protection against them. Hence, measures should be taken to ensure wider spacing of the houses with proper drainage and suitable revetment walls. Here in the busty areas the bearing capacity of the soils and the debris rich in sand particle ranges between 4.5 to 6.6 kg cm^{-2}, corresponding to the strength suitable for the construction of three-storied buildings only[110]. So any construction beyond this limit must be prohibited. Moreover, along the unlined drain courses in the busty, spaces should be left on either side at an angle of 45° with the drain bank, which are unstable zones for construction.

Conclusions

In view of the ever increasing problems of landslides in Darjeeling town, man must be made aware of the possible dangers. It is true that one has to make room for the growing population and in this persuit he has to utilise every piece of land available. But the precautions that have to be adopted should not be negleted. In the town, the revetments are not maintained properly, the weep-holes are chocked and the drains are dumped with garbage restricting free drainage of water. Moreover, the present land-use system should be properly evaluated. The construction of high rise buildings should be stopped immediately. The people should be provided with some alternate source of energy through construction of Mini-hydel projects utilising the springs, which can be the only option to prevent them from cutting down more trees. But above all it is of utmost priority to develop mass-awareness among both the local people and the tourists, so that they become aware of the possible dangers.

5.5 Landslides Along Roads

Introduction

There are a few main arterial routes to Darjeeling - the Hill Cart Road, the Pankhabari Road and Peshok Road via Peshok TE combined with the National Highway 31A along the Tista river. Unfortunately, these have, of late, been seriously damaged by numerous landslides specially during the rainy season leading to the total disruption of vehicular

Photo 19: *Debris slide near Mahanadi Railway Station along the Hill Cart Road (by S.R. Basu)*

Photo 20: *An active mud flow track passing the Hill Cart Road near Gayabari (by S.R. Basu)*

Photo 21: *Slumping of the Hill Cart Road at 37th km post (by S.R. Basu)*

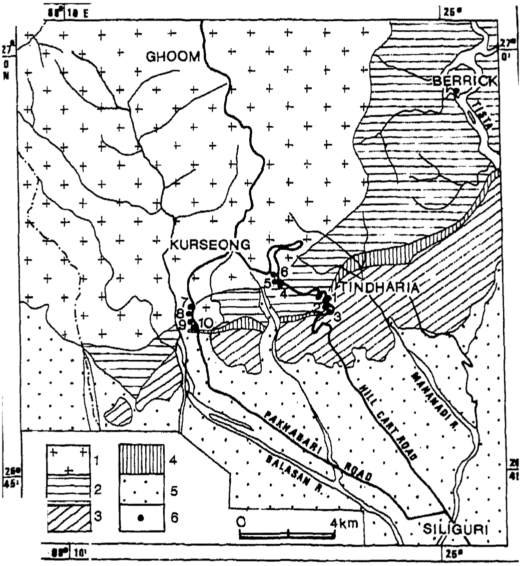
Photo 22: *Failure of protective wall near lower PaglaJhora along the Hill Cart Road (by S.R. Basu)*

traffic between the hills and the plains with the consequent disastrous effect on the transport of goods and tourist operations (Photo 19-22).

Data have been collected through a number of traverses specially during July to September 1982 to 1986, when the mentioned disastrous slips occurred causing heavy damages to railways, roads, houses and public works, after a period of concentrated rainfall[56,57,111].

The geological, pedological and geomorphological surveys of six major landslides spots on the Hill Cart Road and four of the Pankhabari Road, have helped in identifying three problematic sites: around Tindharia, around Mahanadi and above Pankhabari (Fig. 5.16 and Table IV).

The undercutting of slopes due to heavy monsoon precipitation, deforestation, unscientific cultivation and construction activities, are known to combine with rather complex and immature geological formations in the region to generate variety of landslides (Table IV). The landslides in the Tista valley along the National Highway 31A have been dealt separately as their characteristics were compiled mostly from GSI reports (Table IV).



1. Darjeeling gneisses, 2. Daling group, 3. Siwalik group, 4. Damuda group, 5. Quaternary deposits

Fig: 5.16: Location of described slips along roads (numbers - in text and on Fig. 5.17)

Table IV: Comparative study of landslides on Hill Cart Road (1-6), Pankhabari Road and NH4 31A (7-11)

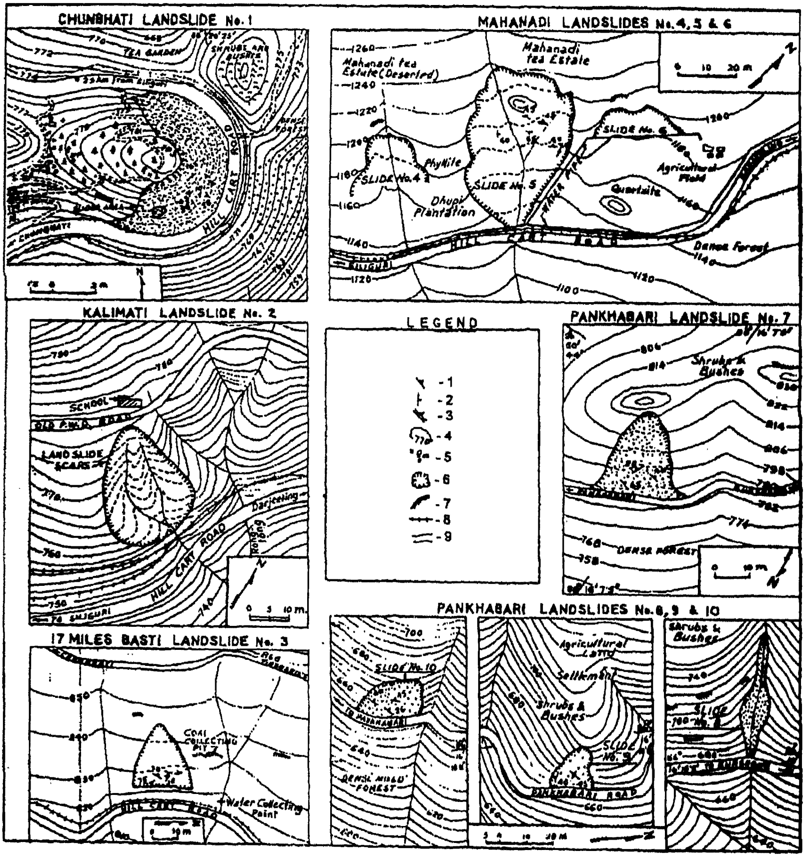
No.	Location, distance and date	Rock types	Type of slides	Type of materials affected	Volume of materials dislodged (m^3)	Causative factors
1.	Chunbhati landslide, 24.80 km North of Siliguri, on 7.09.1986	Sandstone and shale interbedded with thin coal seams	Debris-slide	Fragments of sandstone and chips of coal	1020	Heavy and concentrated rainfall and the removal of basal support by coal quarrying
2.	Kalimati landslide, 25.5 km North of Siliguri, on 23.09.1982	Jointed sandstone interbedded with thin coal seams	Debris-slide	Fragments of sandstones with chips of coal	660	Heavy rainfall and removal of basal support by the removal of coal
3.	17 miles Basti landslide, 26.5 km North of Siliguri on 9.09.1984	Shale and sands-tone	Rock cum debris-slide	Fragments of disintegrated shale	643	Solifluction and removal of the basal support by extension of roads
4.	Mahanadi landslide (1), 36.50 km North of Siliguri on 10.09.1985	Phyllite	Debris-slide along a Jhora	Fragments of disintegrated phyllite	390	Solifluction and gravitational pull on saturated materials
5.	Mahanadi landslide (2), 36.55 km North of Siliguri on 7.09.1986	Quartzite	Debris-slide along a stream	Fragments of Quartzites	12000	Solifluction and passage of surface water to underground routes causing sub-surface erosion
6.	Mahanadi landslide (3), 36.60 km North of Siliguri on 7.09.1986	Quartzite	Debris-slide	Decomposed fragments of Quartzites	300	Solifluction on highly saturated materials on a steep slope
7.	Pankhabari landslide (1), 3.60 km South of Kurseong on 7.07.1985	Highly decomposed phyllites jointed Feldspars and patches of mica schists	Debris-slide	Rock and debris slide, fragmentary pieces of rocks	232	Heavy rainfall increasing pore-water pressure and gravitational pull on the materials
8.	Pankhabari landslide (2), 3.75 km South of Kurseong on 7.07.1985	Decomposed phyllites and quartzites	Debris-slide along a Jhora	Highly decomposed materials combining to form mudflow	919	Salifluction and heavy rainfall on the slopes
9.	Pankhabari landslide (3), 4.00 km South of Kurseong on 7.07.1985	Decomposed phyllites with occasional quartz bands	Rock-fall	Loose, phyllite and quartzite rocks	234	Heavy rainfall and gravitational pull on loose rocks
10.	Pankhabari landslide (4), 4.20 km South of Kurseong on 7.07.1985	Sandstone and shale	Debris-slide	Loose shale and sandstone saturated with water	279	Intense rainfall, solifluction and gravitational pull on loose materials
11.	Berrik slide, 12 km North of Sevok-Tista section of NH 31A on October 1968	Orthoquartzite with bands of phyllites	Rock-fall	Disintegrated phyllites and Quartzite fragments	–	The entire hill slope rendered unstable due to the steepe-ning of slopes by toe-erosion by the Tista river

Major Types of Slope Failures

The following important types of mass movements have been recognised by the investigators: i) slumps, ii) debris slides and iii) earth-debris flows.

i) *Slumps:* A very good example is represented by large slumping slope near Paglajhora (37 km post from Siliguri). The gradual subsidence of the Hill Cart Road for a length of about 500 m, had been noticed since 1966 every year (Fig. 5.17).

ii) *Debris Slides:* The debris slides are generally of greater magnitude and are quite common. Slope failures are found in and around Tindharia and Chunbhati.



1. Schistosity, 2. Bedding, 3. Bedding plane, 4. Contours in meters, 5. Building, 6. Slided area, 7. Old scar, 8. Railway, 9. Road

Fig. 5.17: Landslides along Hill Cart and Pankhabari roads to Darjeeling

iii) *Earth-Debris Flows:* This type of slope failure had often been found in and around Tindharia and Mahanadi in which saturated debris along with big blocks of rocks flow downward to form a channel of its own.

Landslides in and Around Tindharia

This region (in between 24 to 30 km North of Siliguri) is mainly composed of slightly altered Gondwana formation of which sandstone and shale are noteworthy. These have more or less been extended in ENE to WSW direction with varying depths. Small coal seams are few centimeters thick only. Altered quartzite, phyllite, slate and mica schist of Daling formation are found above sandstone (Fig. 5.17). The landslides No. 1 and 2 were identified on the lower sandstone at 25.5 km and 29.33 km respectively from Siliguri on the left side of the Hill Cart Road, whereas the landslide No. 3 has been found on the upper sandstone of Gondwana formation (Fig. 5.17 and Basu and Sarkar)[56].

Here the slightly recrystallised and coarse grained sandstone is characterised by cataclastic deformation which destroyed the clastic texture with intense granulation along ramifying narrow zones of fracture[112]. Alternate thermal expansion and contraction, give rise to vertical cracks within the rock and horizontal beds of rock disintegrate into blocks. Water seeping through such fractures in sandstone helps in decomposing feldspar to form clay minerals which acts as a lubricant for further sliding of rocks which are steeply inclined towards road slide. A few centimetres thick coal seams, interbedded in sandstone hitherto unexposed had suddenly been unearthed after the removal of the surface layer of the soils by intense showers (100 mm in 52 hrs). The local people, suffering immensely due to the lack of fuel, naturally got delighted at the sight of a new source of energy and had a tendency to collect fragmentary pieces of coal, creating large hollows at the crest of slopes. Such human interference readily ruptured the slope stability in case of landslides 2 and 3.

Landslides in and Around Mahanadi

This region (in between 36-37 km north of Siliguri) is composed of altered metamorphic rocks of Daling formation of which quartzite, phyllite, slate and mica schist are important. Due to intense weathering coupled with high rainfall (140 mm in 24 hrs), the earthflows were formed. Water of small springs following over these slides often go underground and perform considerable sub-surface erosion. As a result, subsidence is a common feature in this region. The Hill Cart Road has been very much affected since 1985 and has gone down by 5 to 7 meters disrupting the regular traffic.

Landslides Above Pankhabari

The southern portion (Landslide No. 10) of this region (3-4 km south of Kurseong) is composed of sedimentary rocks (sandstone and slate) of Gondwana formation and the northern portion (Landslides No. 7, 8 and 9) is formed of metamorphic rocks (quartzite, phyllite, slate and mica-schist) of Daling formation.

The apexes of the slides of this region had long been deforested and turned into cultivated terraces by local inhabitants. Such terraces were seldom laid along the contours with proper protection walls. Moreover, these terraces had often been cultivated with potato, ginger and onion which were harvested during September-October, when the monsoon was very much prevalent in this region. This particular practices not only disturbed the cohesiveness of the soil (totally saturated with water) but also made it vulnerable to erosion. Thus, the slope under study remained fully exposed to heavy rainfall (observed after 83 mm of rain in 24 hrs) and was susceptible to both sheet and gully-erosion. As a result fragmentary pieces of rock roll down to cause landslides (Fig. 5.17).

Landslide Along the Tista Valley on National Highway 31A

The National Highway 31A, which takes off from Sivok bridge and runs upto Gangtok, has been affected by number of major landslide enroute. One of the major slides is located near Berrik about 12 km north of Sivok bridge[55]. At this point, the road runs on the right bank of the Tista river. The affected road stretch is about 300 m at an approximate height of 100 m above the road level. The hill slope is steep, around 50°. The river below the road level hits the toe-portion of the slope almost at right angle.

The principal rock types include orthoquartzite with bands of phyllite. The strike of the rock formations is NE-SW with north-westerly dip of about 40-50°. The slide assumed serious proportions during the 1968 monsoons[55]. In areas with phyllite outcrops, the failure, mostly along a curved surface, does not follow any structural plane. During heavy rains the phyllites disintegrate easily and flow down when surcharged with water (debris flow). The entire hill slope has been rendered unstable due to steepening of slopes by toe erosion by the Tista river.

5.6 Landslides in the Lish Basin

Introduction

The river Lish, one of the major left bank tributaries of the mighty river Tista, originates in the Darjeeling Himalaya from Lolegaon at an altitude of 1820 m. It traverses a winding course of about 21 km before its confluence with the Tista. The total catchment of the river Lish is about 70 km^2. The summer rainfall in headwaters reaches 3000 mm.

Landslides and floods are two most severe natural hazards that undermine the economic and cultural progress of the Lish basin. Past history shows a sharp acceleration in the rate of devastating slides occurrences (total number 135, covering an area of 1.5 km^2 in 1929-1930) along with lesser slips leading to a great toll of life and heavy damage to land and property. Recently in 1986-1990 the landslides cover an area of 4.9 km^2.

The present study has been the outcome of a continuous and systematic research since 1980 by a team of researchers under the guidance of the first author (S.R. Basu)[58,59,61-63,113-115].

Landslides in the Darjeeling Gneiss

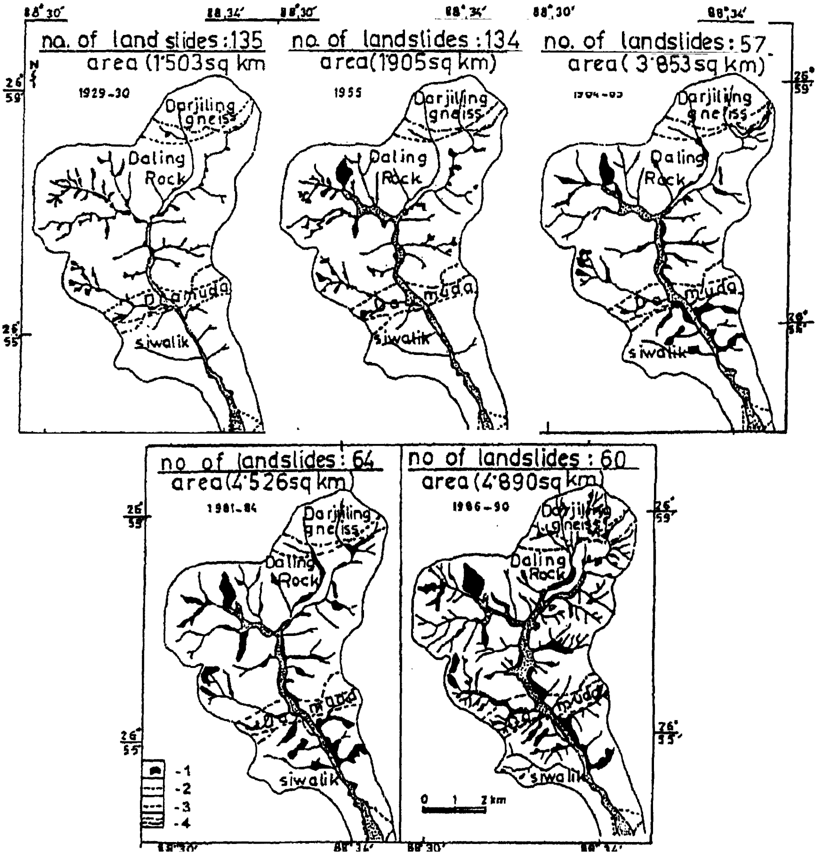
The source region of the Lish is mostly confined to highly metamorphosed Darjeeling-gneissic rocks with total area of 4.98 km^2, composed of foliated gneisses, mica-schists and bands of flaggy quartzites. There are some prominent and other minor joints having steep westerly dip varying from 40° to 70°.

Due to the utmost maltreatment under private forestry, the introduction of the plantation and the expansion of settlements, agriculture and roads, about 40% of the total area of the Darjeeling-gneissic part of the Lish basin have already been deforested. The deforested slopes, which may otherwise maintain the stability of slopes by repelling the direct rainfall of absorbing a part of the groundwater through its root-system, remain exposed to heavy showers and are susceptible to gully erosion.

The total number of slips (mostly minor debris slides) recorded on the Darjeeling-gneissic rocks during 1929-1930 were only 2, covering an insignificant area of 0.015 km², but due to heavy rainfall, the slides registered in 1954-1955 increased to 20 covering an area of 0.0162 km². Later though the total number of slides decreased to 2, their total area increased to 0.0182 km² in 1981-1984. But in 1986-1990 not only the number of slides has increased to 10, but also the total area to 0.20 km² (Fig. 5.18).

Landslides in the Daling Series

The Daling series represented by purple slates, quartizites and crumpled phyllites, cover an area of 31.52 km² and lie south of the Darjeeling-gneiss.



1. Landslides, 2. Forest boundary, 3. Geological boundary, 4. Floor of braided river channel

Fig. 5.18: Landslide prone areas in Lish basin from 1930 to 1990 (after Basu and Ghatowar[113], partly changed)

Near the ridge crest the regolith is about 3-5 m thick and the lower slopes are generally covered with boulders.

This area has long been deforested and turned either into cultivated terraces or settlements. Such terraces are seldom laid along the contours with proper protective walls. Moreover, these are often cultivated with potato, onions and ginger, which are uprooted in September-October. This particular practice changed the cohesiveness of the soil, and make it vulnerable to erosion.

The total number of major and minor slips occurred on the Daling Series during 1929-1930, were 115 covering an area of 1.330 km^2, and in 1954-1955 the area increased to 1.710 km^2 with the number of slides remaining the same. In 1964-1965 the total number of slips had decreased to 40 because of the merging of some of the minor slides with the major ones but the total area under slides had gone up to 2.562 km^2. Such a trend of areal extension had also been followed in 1981-1984, the area being 2.953 km^2. In recent years (1986-1990) though the number of slides has slightly decreased to 40 but the area had gone up to 3.03 km^2 occupying 9.55% of the total area. Some of the major slides found on the Daling Series are responsible for supplying huge amount of debris to the channel of the Lish.

1. *Pabringtar Landslide*

This landslide on the right bank of the Lish river has affected the steep slopes of the Daling rocks at an altitude of 1200 m about 2 km SE of Samthar village. The reason behind such a catastrophic slide seems to be structural as the joint planes in quartzites dip less steeply than the slopes of the hills[48]. This area receives especially heavy rainfall due to its southern exposure. The rain water rushing along such steep and deforested slopes ultimately gave rise to such a huge slide whose area has gradually been increased since 1929 (Fig. 5.18):
1929-1930 - 0.078km^2, 1954-1955 - 0.281km^2, 1964-1965 - 0.312km^2,
1981-1984 - 0.375km^2, 1986-1990 - 0.482km^2.

2. *The Yangmakun Landslide*

Near Yangmakun village a number of landslide scars are visible along the right bank of the river Lish, among which Yangmakun is the largest. It is said to have been developed by the earthquake of 1934. After twenty years in 1954, it not only damaged the river severely by depositing about 1.98 million cubic metres of debris, but also gave rise to a 14 m high natural dam across the river. Water charged debris loosened from the Pabringtar landslide[48] mentioned above seemed to have brust opened this dam. The geological composition of the local phyllites alternating with quartzites and dipping at a smaller angle than that of the hill slopes, has definite bearing on continuous expansion of this particular slide other than the initial causes of earthquake and gully erosion.

Landslides in the Damuda Series

The coal bearing Damuda rocks lie in an E-W fashion in between the Daling thrust on the north and the Main Boundary Fault to the south. As a result of thrusting, Damuda Series is overridden by the older Daling rocks and is underlaid by young Tertiaries. There are 5 landslides covering an area of 0.192 km^2 within this narrow stretch of 3.15 km^2. Many of the extensive landslides are due to unscientific mining operations in the coalfields. Haphazard digging of the untreated soft and quite friable coal have produced slips and created conditions for the quick removal of top soil[50,62].

Landslides in the Siwalik System

The Siwalik sandstones, mudstones and conglomerates along with the bands of marly shales cover an area of about 12.44 km^2 in the Lish basin. During 1986-1990, there were 6 landslides covering an area of 1.47 km^2.

The slightly recrystallised and coarse-grained sandstone is characterised by cataclastic deformation, which destroyed the clastic texture with intense granulation along narrow zones of fracture. Solid masses of horizontal beds of rocks disintegrate into blocks. The high rainfall seeping through the pore-spaces of the coarse textured sandstone decomposes the feldspar to form clay minerals, which acts as a lubricant for further sliding[56].

At the apexes of the slide zones, vulnerable conditions have naturally developed at depths of 20-30 cm below the surface where clay predominates with a good amount of organic matter, high water holding capacity and volume expansion. The apexes of the slides have long been deforested and are susceptible to both sheet and gully-erosion. The percolating rain water increases the hydrostatic pressure within the soil. Internal friction sets in and the soil ultimately loses its cohesion. Thus, rill-cutting as well as gully-erosion starts. Such conditions have further been intensified by toe-erosion caused by the Lish river.

Consequences of Siltation of the Lish River Bed

From the above discussion of the causes of landslides on different geological formations of the Lish basin, it becomes apparent that the basin has been suffering since 1929 partly due to natural factors like inherent geological structure, steep slopes and heavy monsoonal downpour but more due to anthropogenic factors like deforestation, unscientific mining and agriculture. In 1986-1990, it has been found that there are 60 active landslides, which amount to 6.8% of the total area. Most of the landslides have never been treated with proper protective measures. The expanding landslides add huge amount of debris to the river each year. This has been proved by the increase in the area of bars and shoals in the Lish river from 11.406 km^2 in 1929-1930, to 14.468 km^2 in 1981-1984 and 16.718 km^2 in 1986-1990. The channel has developed a braided pattern which may be attributed to both incompetency and incapacity of the river[116]. This causes the bed of the river to rise constantly at a rate upto 50 cm per year at the bridge point of National Highway A31[60,63]. The aggradation is continuously progressing upstream and now it starts only 2-3 km distance from the watershed in the headwater area (Fig. 6.22).

The cross-sectional area thus decreased and causes the water to spill causing floods. The narrow road and railway bridges across the river and the pillars supporting these are also considered to be the causes of the entanglement of the uprooted trees interrupting the natural sediment load and thereby aggravating the flood situation.

During the devastating floods of 1954, two spans of the Lish road bridge had been slightly damaged while the arches had almost been filled up with debris[48]. The spans were ultimately dismantled and replaced by a new bridge.

The settlements and tea gardens of Bagrakot and Washabari were partially destroyed by the washing away of the Lish road and rail bridges by the swirling flood waters of 1968. The floods of September 1983, though of minor nature, caused considerable damage to crops cultivated on the floodplains around the confluence of the river with the Tista[115].

Thus, it can be concluded that the natural equilibrium of hillslopes of the Lish basin has so seriously been disturbed that during rains innumerable landslides are caused releasing huge amount of sediments to the river, which in return is unable to transport them.

5.7 Ambootia - an Example of the Active Landslide Valley

Environment

The Ambootia landslide developed after October rain in 1968 in one shallow *khola* channel at the southern margin of the Ambootia T. E. It is located on the left side of the Balasan river valley only 4.5 km from the border of the Himalayas. The landslide starts about 200 m below the ridge rising 1350 m a.s.l. and runs 625 m down to the Balasan valley. The specific feature of this "landslide valley" is its form and dynamic nature in close cooperation of gravitational processes and linear downcutting, which are continuously active, in contrary to other stabilised smaller slides[65].

This area is built of gneisses, mica schist, chloritic schists, etc. belonging to Darjeeling group[21]. These are inclined mainly 30-50° towards N-NNW, deeply weathered and with high density of joints. The pre-landslide slope consisted of 3 parts. The upper portion inclined at 15-25° was dismembered by shallow depressions and one deeper hollow (to the north). The middle flat part elevated at 900-950 m a.s.l. was occupied by colluvial fan inclined at 3-6° towards W and NW built of 30 m thick silty-sandy deposits with gravel and stony layers. The lower portion forms steep valley side dissected by shallow side valley 30-100 m deep (after old topographic map). The existing landslide area is bare or covered by pioneer vegetation with several patches of trees. Before 1968 (Fig. 5.19) lower part was covered with shrubby jungle and bamboo, the middle and upper was occupied by the village with orange orchards and gardens.

1. Jungle, 2. Scrub jungle and bamboo, 3. Tea plantation, 4. Line (village with gardens), 5. Thatch, 6. Existing roads fragments, 7. Damaged road, 8. Contour of existing landslide valley, 9. Position of main niche in 1983 and 1987, 10. Colluvial fan active in 1968 and 1983, 11. Perennial and seasonal streams, 12. Spring

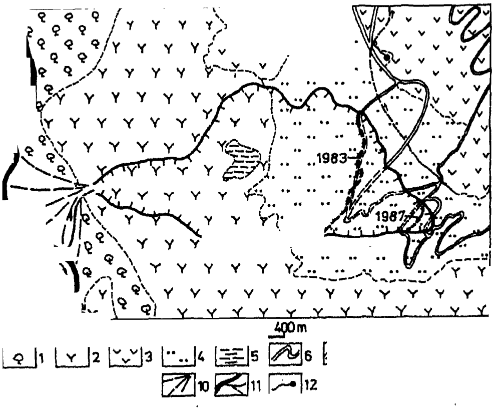


Fig. 5.19: Previous land use and roads in the region of the Ambootia landslide valley 1968-1989 (after Froehlich et al.[65])

Morphology

The Ambootia landslide valley extends for 1300 m (Photo 23-27). The upper niche begins at an elevation of 1065 m a.s.l. and below waterfalls at 480 m a.s.l. the fan zone begins (Fig. 5.20 and 5.21). The width of the landslide valley reaches 625 m in the middle part. The whole slide occupies about 56.5 ha. It's depth increases from 10-20 m in the upper part to 200-270 m in the middle and drops to below 100 m in the lower part. The entire form has now a shape of gully-canyon cut in bedrock, with high gradient and waterfalls, its slopes are modelled by various mass movements (see geomorphic map and profiles, Fig. 5.21,

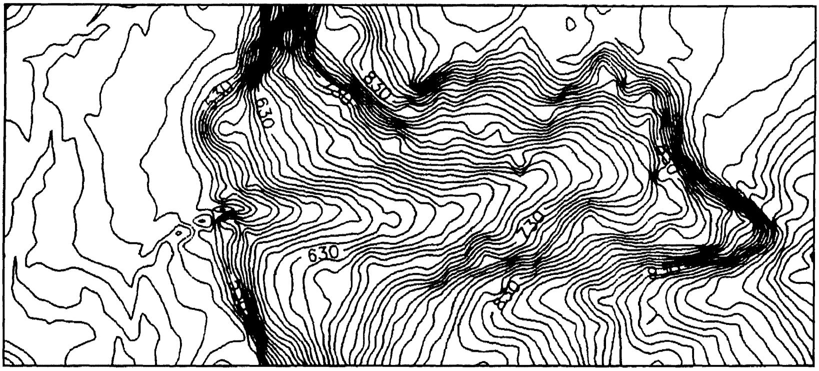


Fig. 5.20: Hypsometric map of Ambootia (based on maps and nivelation – compiled by P.Prokop)

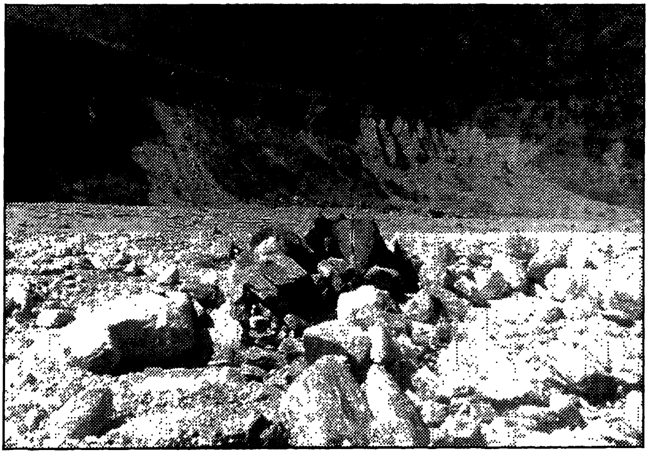


Photo 23: *Outlet creek of the Ambootia landslide valley affected every year by minor debris flows. In the back the undercut large colluvial fan created in 1968 and 1983 (1989) (by W. Froehlich)*

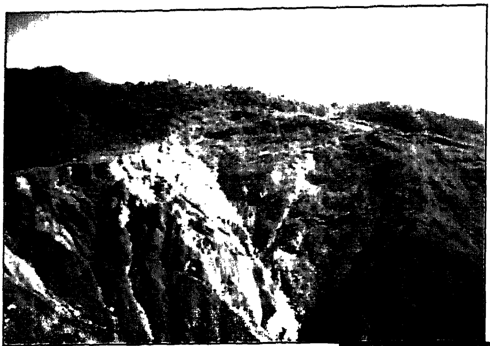
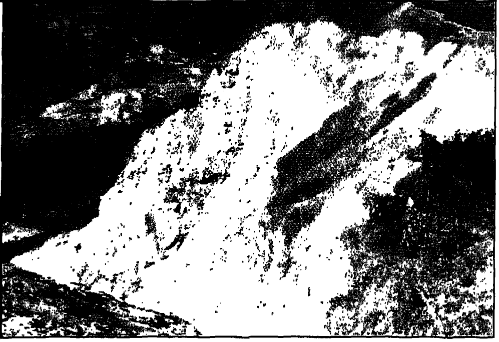


Photo 24: *Upper part of the asymmetric Ambootia landslide valley. On the left margin of the extensive proluvial fan (1998) (by L. Starkel)*

Photo 25: *Middle part and steep right slope of the Ambootia landslide valley (1989) (by L. Starkel)*



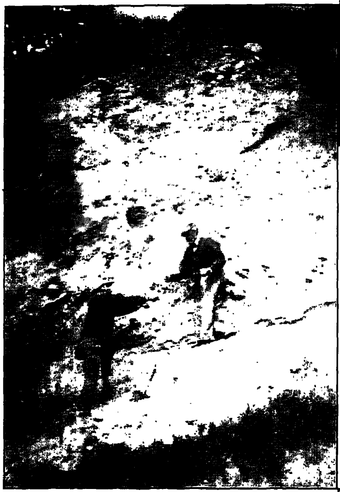
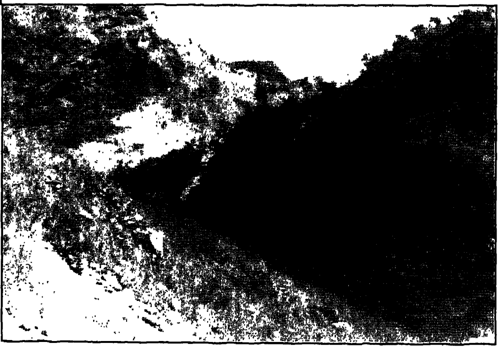
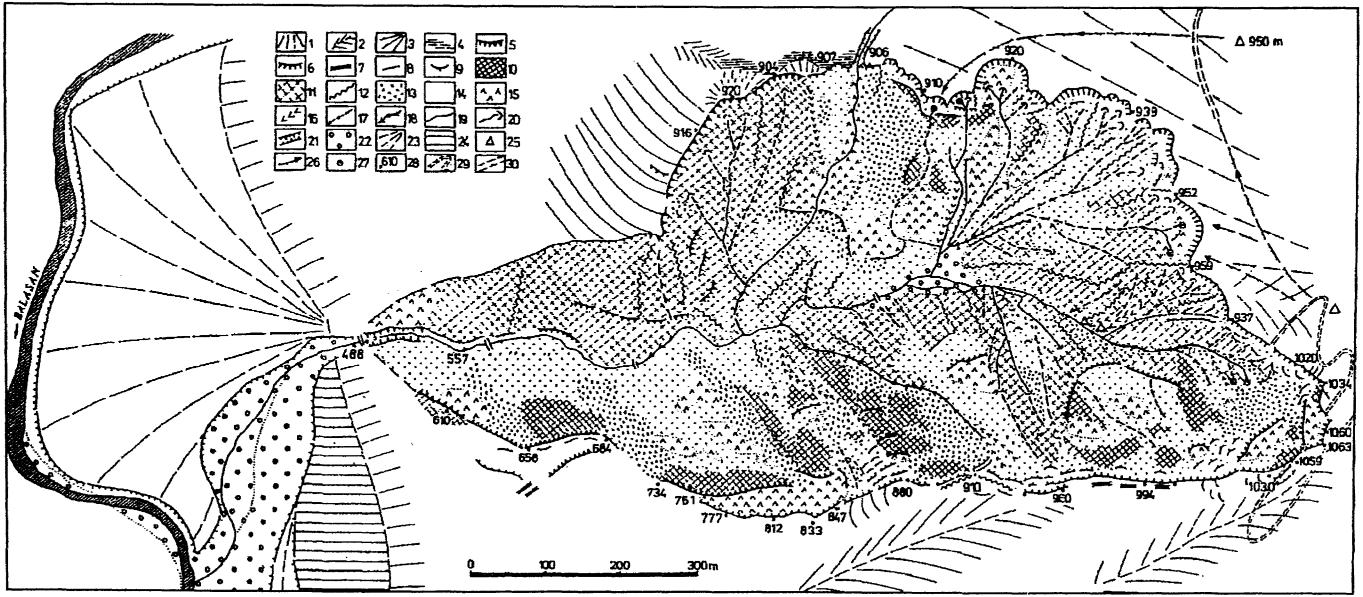


Photo 26: *Proluvial stratified sands, gravels and boulders exposed in the northern edge of Ambootia landslide valley (1996) (by L. Starkel)*

Photo 27: *Outlet of the Ambootia landslide to the Balasan river valley (1989). Ten years ago the retreating scarp still don't reached the ridge axis (by W. Froehlich)*





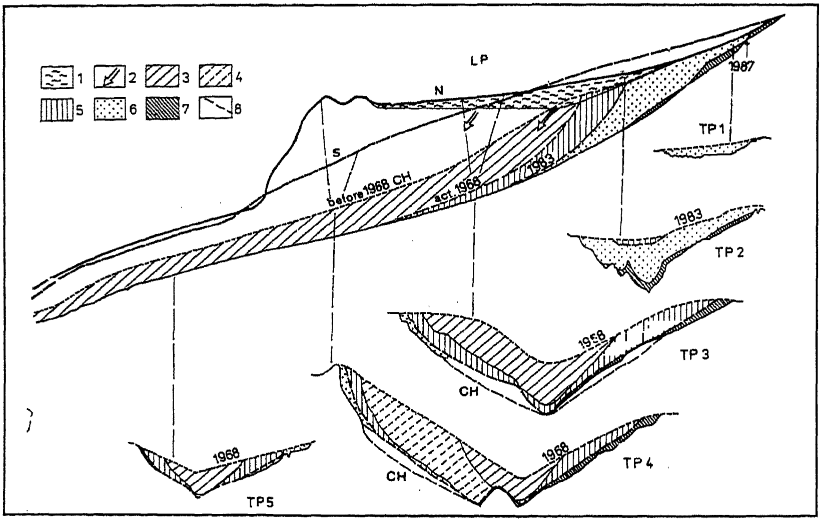
1. Steep hillslopes, 2. Small valleys outside landslide, 3. Surface of old culluvial fan, 4. Bottom of inactive valley, 5. Landslide niches in bedrock, 6. Niches in loose deposits, 7. Landslide grabens, 8. Cracks, 9. Slump steps, 10. Penestructural rocky surfaces, 11. Other rocky slopes, 12. Narrow ridges, 13. Coarse block fields and talus, 14. Fine block fields and talus, 15. Revegetated debris slopes, 16. Chutes formed by debris flows without water, 17. Chutes with seasonal runoff, 18. Chutes and gullies with debris and perennial run-off, 19. Channels with perennial stream, cut in bedrock. 20. Spring niches, 21. Canyons, 22. Deposition of debris in channels and on fans, 23. Dissected colluvial fan of the Ambootia landslide valley, 24. Fragment of older fan in the Balasan valley, 25. Places of experiments with luminofores, 26. Directions of surface drainage, 27. Springs which showed coloured water, 28. Elevation in meters, 29. Road, 30. Artificial channel

Fig. 5.21: Geomorphological map of the Ambootia landslide valley (surveyed on scale 1:5000) (after Froehlich et al.,[64,65]*)*

5.22). The uppermost part is worked by slumping and sliding upto 10-20 m deep (Photo 24). Niches are accompanied by frequent active cracks. The dip slope at the left inclined at 25-45° has a straight or convex profile. In the upper part bare rock is exposed, whereas the lower part is covered with creeping blockfields with revegetated inactive fragments in between. The retreat is signed by fresh crevices up to 4 m deep following the upper niche.

The northern right slope in the middle part of the valley is cut in colluvial deposits overlying deeply weathered rocks (Photo 26). In colluvia are cut two-storied niches of slumps issuing out water. Downslope are chutes of debris flows cut in bedrock, separated by sharp crests or flattening revegetated more and more by herbs, shrubs and trees. The central - lower segment of right slope above 300 m high is represented by rocky walls, further down with thin debris fans dissected by chutes (Photo 25).

The floor of the main gully is changing every year. Characterised by big boulders and waterfalls, the floor is often transformed by frequent debris flows and rock avalanches, which gave rise to a colluvial fan



1. Thick colluvia, 2. Direction of high seepage pressure, 3. Masses removed in various phases: 3. Early phase of October 1968 event, 4. Late phase of October 1968 event, 5. Between 1968 and 1983, 6. 1983-1987, 7. 1987-1989, 8. New chutes cut in older landslide slopes

Fig. 5.22: Reconstructed phases of landslide valley evolution (after Froehlich et al.,[65])

above 100 m wide and 15-20 m high in 1968 and remodelled again in 1983 (Photo 23, 27).

Hydrology

North of the main niche there exists a V-shaped valley cut in the bedrock with periodical stream. In 1986 after extending of landslide, an artificial channel was built to take all the water flowing from the upper slope and gushing from the spring towards the flat depression extending to the north.

Over the landslide valley itself during the autumn survey there were registered dozens of springs, mainly concentrated in two horizons of colluvial deposits of the right slopes as well as in the main axis of the landslide valley and even on the rocky slopes. In winter number of springs is restricted to a few fed by thick colluvial deposits and underlying jointed bedrock.

In October 1989 we observed in the northern V-shape valley a desiccation of the creek (having upstream more than 10 l sec^{-1}) and appearance of water 300 m downstream again. The luminophore were introduced in the upper creek and in the spring outflow. After 10 hours the coloured water from upper creek appeared in the springs in the upper part of landslide valley at the base of colluvium as well as flowing out from jointed bedrock even south of the main landslide gully. The coloured water from spring appeared in the niches further to the NW. But coloured water never appeared in the canal downstream - the source of that water was probably from deeper horizon, supplied by the upper slope. These experiments helped to calculate the rate of subsurface flow of order 5-12 m h^{-1}. It is probably much higher during heavy rains.

The uppermost niche is fed also by concentrated flow over the road pavement (several segments of abandoned roads are present there). In the calculation of water supply to the landslide the rain falling on its surface cannot be omitted as well as flat area covered by colluvial deposits, where measurements of the infiltration rate were carried out. There fluctuations of rate from 4 to 25 mm min^{-1} were observed depending on lithology and land-use (see Chapter 5.2).

Stage of Evolution of Landslide Valley

The present day relief and variety of processes reflected in changeable geomorphic features indicate a complex history of various parts of the landslide area (Fig. 5.22). A shallow V-shaped valley existed in the lower part before October 1968. During continuous rain reaching 890 mm (registered at 1.2 km distance to the north) landslide (debris flows) were triggered off. The saturated thick colluvial and weathered rock underneath, slumped down over the former valley head and a big debris tongue carved out a channel at least 30-60 m deep. The mass of the order 10-15 million m^3 was partly deposited as a fan in the Balasan valley floor. The undercutting of gully sides caused formation of big rockfalls on the right and consequent slips and flows on the left side.

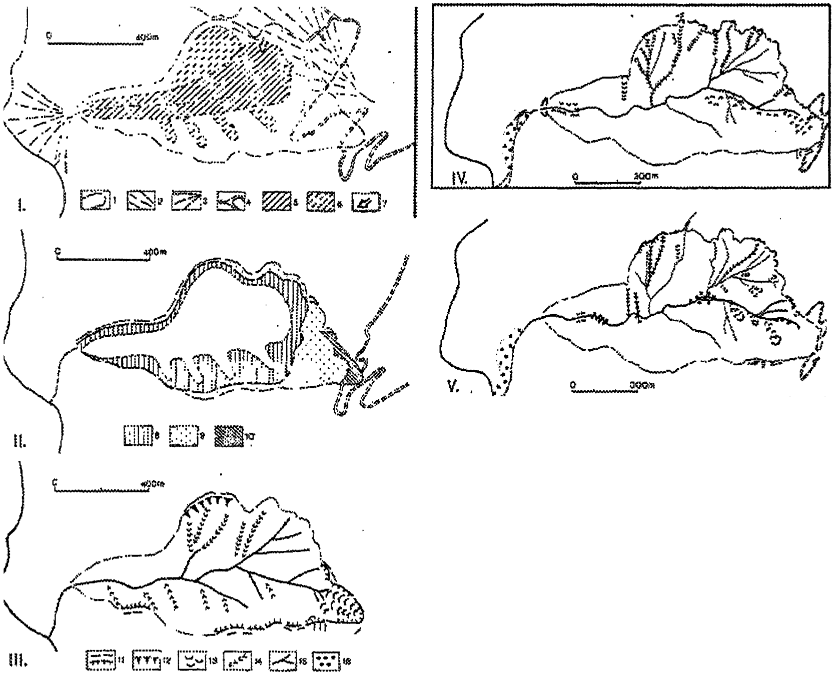
During the following years the landslide subsequently expanded, especially by retreat of right niches fed by groundwater in the colluvia and retreat of upper part due to deepening of the main channel (Photo 24). An acceleration in mass movement and deepening of main channel was caused by continuous 400 mm high rains between 25-30 June 1983 when many houses and roads were damaged and the colluvial fan in the Balasan valley built up again (Fig. 5.22).

Between 1983 and 1989 (year of detailed survey) the undermining of the upper part by chutes continued resulting in the retreat of upper niche causing the permanent damages to houses and main road leading to Ambootia. Slumping and falling on the right side and sliding on the left side followed. A simultaneous modification of chutes and main canyon by the flowing water continued for at least 6 months along with episodic debris flows. From 1989 upto January 1996 several visits were conducted to Ambootia. The rainfall characteristic for last 10 years did not show any distinct events (Fig. 4.1). During that time a very slight reactivation of the upper niche was registered with a continuous slow sliding on the left consequent slope and small slumps on the niches were carved in the colluvial deposits (Fig. 5.23 and Photo 24). Only the right vertical wall is active in the western part, where big rockfalls in the summer of 1995 were registered (Photo 25, 27). In contrast to the gradually vegetated slopes, the bare bottom of the valley undergoes transformation in every summer, especially the lower canyon sector, where the debris flows alternate with gullying and waterfalls.

Tendency of Evolution and Prediction

The existing deep landslide valley in Ambootia is the effect of specific combination of processes acting since 1968. Total overdeeping of shallow old valley reached about 120 m in the middle. The leading factor in its creation was the oversaturation of the highly elevated water reservoir in thick colluvia, which also later supported their reactivation. The high gradient included the linear erosion as the second factor. This erosion again provoked the supply of material from the slopes and this is a critical factor in the further expansion of the landslide valley (Fig. 5.22, 5.23).

At present the geomorphic parameters of slopes had reached the stage of an unstable equilibrium. Each extreme rainfall may cause however some relatively small changes in their morphology. Between



1. Main edge of landslide, 2. Old plain covered by colluvia, 3. Colluvial fan, 4. Road, 5-6. Masses removed during Oct. 1968 event: 5. In early phase, 6. In late phase, 7. Direction of subsurface water flow and debris flows, 8. Masses removed between 1968 - 1983, 9. As above 1983-1987, 10. As above 1987-1989, 11. Active niches and cracks, 12. Rockfalls, 13. Sliding masses, 14. Block streams (main), 15. Chutes and canyons undergoing downcutting (main), 16. Deposition of coarse debris

Fig. 5.23: Reconstructed spatial changes in evolution of the landslide valley: I–In 1968, II–from 1968-1989, III–Parts actively modelled in 1989, IV–Parts active in February 1991, V–Parts active in January 1996

1989 and 1996 the continuous progress in revegetation of the surface is visible. In 1996 about 80-90% of landslide area was covered by relatively dense vegetation cover, among which 20-30% were bushes and patches of open woodland. The suggested reforestation and engineering works[64,65] started in the neighbouring areas to the landslide. The protection of the whole landslide surface against overgrazing and tree cutting has also begun. The feeding of the landslide valley by the groundwater coming from the upper slopes should still be registered. The old canal should be rebuilt into an impermeable one, cutting the infiltration of water into the ground. The hydraulic parameters of such a canal should be adapted to the large discharge and heavy bedload during extreme events. Also, the drainage from an old road upslope of the upper niche should be turned to a canal in the north. For better protection all houses using water pipes still located closely to the upper niche should be removed.

The landslide valley of Ambootia will leave in the future a great scar on the mountain slope. In the Darjeeling Himalaya many such inactive scars may be identified on the slopes, even just at the opposite side of the Balasan river similar niche is present. The continuous observations in Ambootia lead to the conclusion that for the formation of such large gully- scars on the slopes, only catastrophic landslide events are not sufficient, but relaxation time and long-time transformation are equally important[35,103,117-119].

5.8 Role of Mass Movements and Tendencies of Slope Evolution

The young slopes of the Darjeeling Himalaya due to their steepness and frequent undermining by rivers are exposed to the various types of mass movements. Their lengths exceeding frequently 1000 m and their uneven profiles (in both transects) facilitate both the removal of regolith from the upper slopes to the river channels as well as the short-term storage of colluvial deposits on the less inclined slope benches.

In such denudational balance much more important is the rate of weathering and soil formation, which over the metamorphic rocks and under the monsoonal climate is relatively high. The recovery of soil cover may follow after several decades, excluding steep portions where the bare, more resistant bedrock is exposed. Therefore, on the gentle slope benches more loose material is produced and these may be removed subsequently due to higher water storage. On the other hand steeper scarps produce an accelerated run-off of water and mass displacement.

The rate of processes is often accelerated by various types of human activities[120]. The most extensive is deforestation, which may be of various character. The cutting of older trees on steeper slopes in the tea gardens combined with overgrazing may lead to total obliteration of vegetation or turn the area into dense thickets. Only the gradual destruction of the dense root system will lead to the initiation of shallow slides and gullies. This will be further accelerated by cultivation on slopes.

In the Darjeeling Himalaya two main types of slope transformation by cultivation may be distinguished. The first one is the tea plantation, forming more or less close canopy on the slope upto 25-30°. Their root system being about 1-2 m deep reduces the depth of sliding surface.

The undercuttings along the roads play an important role in the promotion of mass movements (Hearn and Jones[121] and Photo 6, 19, 20). The saturated loose material is exposed to slumps and rockfalls. Especially dangerous are the road segments passing though the slope gullies with waterfalls. Small or larger quarries, the coal mines from Lish and Gish basins play a similar role in undermining of slopes. Finally among various human activities the overloading of slopes by multi-storied concrete buildings can not be overlooked, especially in Darjeeling and Kurseong towns (Chapter 5.4).

During heavy rains on the slopes several thresholds have to be crossed, before an extreme event takes place. The overland flow is very rare due to high infiltration rate and is restricted to rains passing the intensity 1 mm min^{-1}. The seepage pressure may be very high with rainfalls exceeding 300-500 mm in one day and with the intensity of 40-60 mm h^{-1}. This leads to liquefaction of soil and formation of mudflows and debris flows[1,66]. Their starting point can be a scarp or a undercutting, or storage of water in a shallow slope depression (Chapter 5.3).

For the understanding of the rate of slope evolution a critical question is frequency of extreme events producing new gravitational processes. The continuous rains of 2-4 days duration on a regional scale have a recurrence interval of 20-40 years[66]. The local heavy downpours exceeding 200-250 mm or continuous rains between 300-500 mm have a recurrence interval of several years, but the transformation of slopes by them is either localised to vulnerable break points or restricted to a few sq. km only (Fig. 4.5).

In the slope evolution an important role is played by the inter-extreme periods during which usually it follows the revegetation of bare niches, channels and tongues by grasses, shrubs and bamboo forming finally dense thickets (Photos 28, 29). In the tea gardens the shallow earthflows were replanted by new tea bushes after several years.

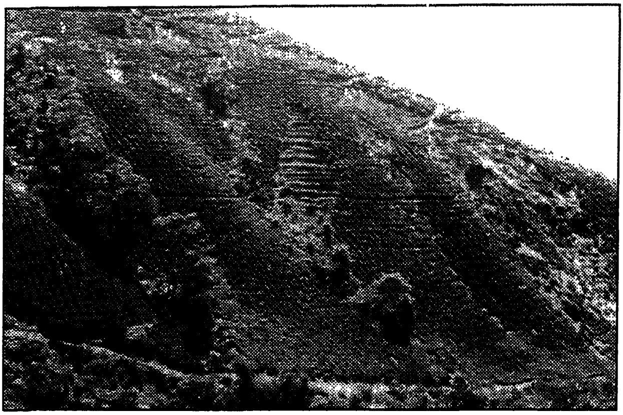


Photo 28: Debris- and earth-flows from October 1968 in Phubsering T.E., later stabilised and again transformed in tea plantation (1984) (by W. Froehlich)

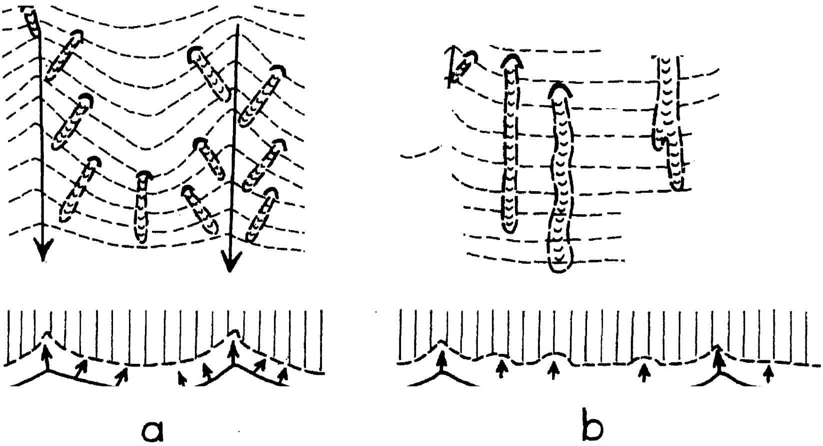
Photo 29: The nursery located in the depression eroded by the earth-flow on gentle slope in Bannockburn T.E. (1986) (by W. Froehlich)

But the formation of a new soil cover, conditioning new mass movements, needs at least several decades. This has been proved by the absence of new flows or gullies in October 1968 over the debris flow tracks formed in 1950[1].

The more frequent reactivation has been observed only in the gullies with seasonal outflow or on steep segments supplied by permanent or episodic springs during downpours (observed at Bannockburn TE). The Ambootia landslide valley is the special case, still active after 1968 event due to high water storage in the thick colluvial deposits (see Chapter 5.7).

The other factor which can not be overlooked are the earthquakes registered in the Darjeeling region in February 1849, June 1877, June 1930 and January 1934.

The young slopes of the Darjeeling Himalaya, the convex as well straight ones in their general shape, controlled by channels changing down valley show a differential backwearing tendency. This tendency is realised in two different ways after the October 1968 event (Fig. 5.24, cf. Ergenzinger[118]).

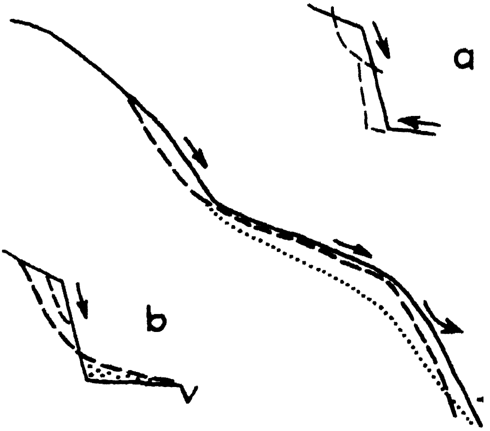


a–With participation of linear erosion, frequently dissecting the slopes and directing the mudflows,
b–By superficial degradation it remains the flat slope surface (by spersely dissected slopes)
At the top the contour - lined slope surface with mudflows, down the transversal slope sections indicating the tendencies of slope evolution

Fig. 5.24: Two ways of valley side formation during catastrophic rainfall (independent of lateral erosion) (after Starkel[1])

In the first place is the continuation of progressive dissection by existing gullies and formation of denser network by the development of new debris flows and mudflows on the slopes (Photo 10). In gradually expanding gully heads, it may develop occasionally the larger landslides and rockfalls. Such large niches are frequently preserved in the landscape, leading finally to the reduction of interfluves into narrow ridges.

On the less dissected and deforested slopes, the removal of weathered rock and backwearing follows by the formation of shallow mudflows and debris flows. Some of them may reach the valley floor, but more frequently the flowing mass is deposited on the more gentle segment of slope and wait for the next extreme event to carry it further down (Fig. 5.25). The calculations made after 1968 event indicate that in the areas of tea gardens upto 20-25% of total slope surface was denuded, which indicate the mean denudation of slopes by 20 cm during one extreme event[1]. The additional stimulus on the steep valley sides of large rivers is the lateral erosion and formation of landslides and gullies extending upslope on erosional edges. In such cases all the eroded material is removed by the river.



a - Simple slope developing by lateral erosion and mass movement, b - Simple slope retreating by mass movement with agradation at the base (usually on the terrace plain), c - Step - like slope, typical for many valleys. Retreat of free - face with help of erosion more intensive than degradation of gentle segments by mudflows

Fig. 5.25: General tendencies of slope evolution in Darjeeling Hills (based on Starkel[1])

6

FLOODS, SEDIMENT LOAD AND CHANNEL FORMATION

6.1 Geomorphic Characteristics of Basins and River Channels of Various Order

The more detailed characteristic of river catchments and channels is needed for the better understanding of run-off and sediment load, as well as of formation of channel, and floodplains.

The typical feature of this region is the dendritic pattern of streams. In the valley head the concentric pattern of several streams is frequent (Fig. 3.7). In the frontal part of the mountains beside larger rivers with tributaries there are many smaller creeks with elongated catchments and rare tributaries.

Due to the insufficient detailed maps the characteristic of stream orders after Horton's classification is not presented. In the upper courses, the number of 1-st - 2-nd order streams is high. For instance, at 8 km length of the Rangnu or Pachim creek it reaches 20 streams. The geometric parameters of river channels change sometime very quickly downstream with length of the stream[122]. Therefore, channels for catchments of various size and river length will be described below.

The headwater streams are located either in the circular valley heads or on the slopes (Photo 7, 13). These streams run single or parallel. On the long slopes (1-2 km) they join together. These are either located in the distinct valley depressions cut in the bedrock and colluvial deposits or a shallow channel is cutting directly a flat slope surface. The gradient of such stream, sometimes above 1 km long, is similar to the slope gradient (30-100%), but frequently with several steps, controlled by the resistant beds. The width of the channel fluctuates between 1 to 10 meters, the sections cleared of debris alternate with heaps of big boulders, originating from rockfalls or debris flows. Sometime at the outlets of gullies or at the terrace benches of higher order streams are formed torrential fans, being dissected during extreme events.

The channels of creeks of 2-4 orders are connected with the catchments from 3-5 upto 20 km^2. Of that size are the described reaches of Posam, Jepikhola and Rangnu creeks (Table V, Fig. 3.7 and Photo 30-34). Their channels of the length of 4-10 km have uneven gradients with steps. The waterfalls and rapids are connected with great blocks up to 10 m in diameter. Their mean gradient fluctuate between 15 and 5%, the levelled section is below 10%, but the rapids reach upto 30% and more. The last ones do not pass one quarter of the total length. The channel floors are 3-10 m wide and incised 1-7 m in the valley bottom, 20-100 m wide, flooded during extreme events. This bottom is built of coarse alluvium composed of boulders 2-5 m in size and gravels of sandy matrix.

Photo 30: *The valley floor of the Rangnu creek totally transformed by debris flows during October 1968 event (December 1968) (by L. Starkel)*

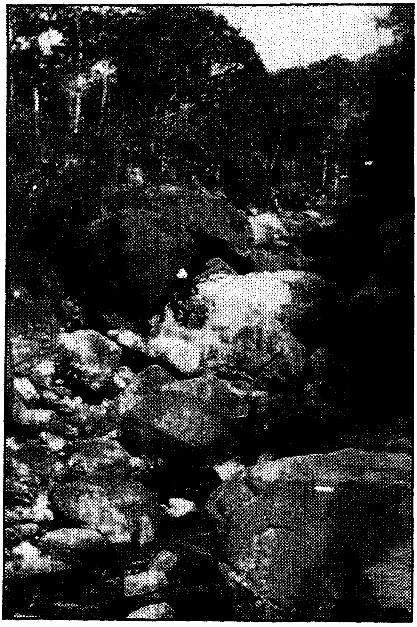


Photo 31: *Revegetated valley floor and incised channel of the Posam creek (February 1984) (by W. Froehlich)*

Photo 32: The Rangnu creek channel upstream of main cross-section in November 1986 (by W. Froehlich)

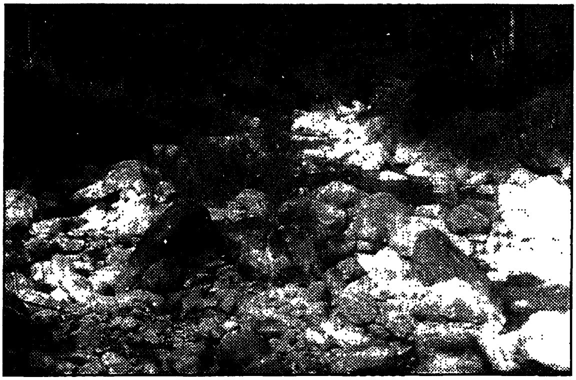


Photo 33: The Rangnu creek channel downstream of main cross-section in November 1986 (by W. Froehlich)

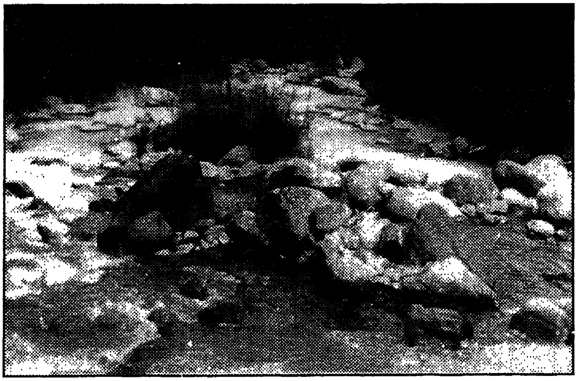


Photo 34: The Rangnu creek channel at the same place as above in September 1987. The boulders upto 0.4 m have been replaced (by W. Froehlich)

The valley floors of large rivers and their channels have well-developed elements and will be described separately. The main difference exists between the transit Tista valley (and its tributaries) and the river valleys dissecting the mountain front (like Mahananda, Balasan and Lish).

In the Tista basin the sinuous middle reach of the Little Rangit river of length 16.5 km has been studied. In this segment the 5% gradient and 10-20 m wide river channel is cut into coarse debris filling the valley floor of 100-200 m and elevated 2-7 m above the low water level (Table V).

In the lowest reach of the Great Rangit river the sinuous channel with gravely-sandy point bars is bordered by steep valley sides with undercuttings (Photo 4). The total width of channel do not exceed 200 m. At the junction with the Tista, river bars form a fan, which changes its shape every year.

The Tista river downstream of the junction with the Great Rangit flows in sinuous or meandering incised valley floor having a width 200-500 m. The reaches cut in the bedrock alternate with reaches cut in coarses boulders (Photo 35) or with wider reaches with several steps of gravel-sandy bars. The most extensive is the terrace 5-7 m high, partly sandy, partly covered by pioneer plants. The width of the channel

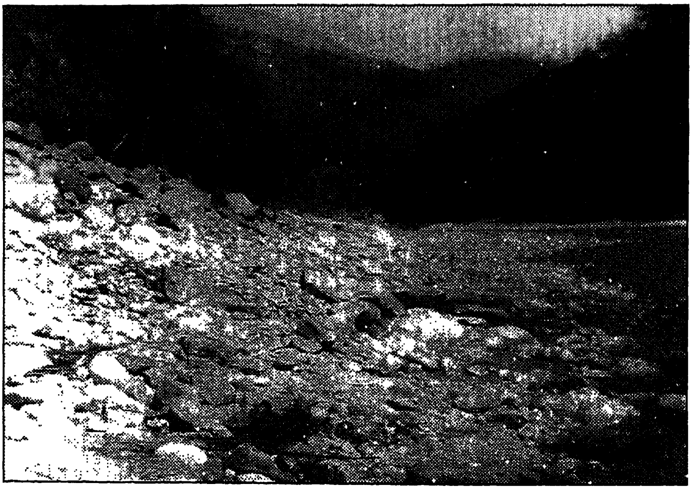


Photo 35: The right bank of the Tista river built of big boulders delivered by the Peshok Jhora creek (1987) (by W. Froehlich)

Table V: Morphometrical characteristic of some surveyed catchment basins

Catchment basin (locality)	Posam (Poobong T.E.)	Pachim (Ringtong T.E.)	Rangnu (Bannockburn T.E.)	Little Rangit	
				upper segment	middle segment (near Pul-Bazar)
Catchment area in sq. km	5.3	9.0	33.1	–	–
Length of main river in km	1.9	5.1	8.1	6.3	16.5
Total length of creeks, dissecting slopes deeper than 50 m	1.3	–	39.0	–	–
Total length of creeks, incising slopes less than 50 m	5.5	5.7	11.4	–	–
Total density of drainage system (valleys) in km/sq. km	1.641	1.200	1.764	–	–
Relative heights in valley head (m)	–	700	800	900-1200	–
Relative heights in lower segment (m)	1350	300-500	100-1250	–	600-1400
Gradient of main river in percent (upper segment)	50	40	24	25	–
Gradient of main river in percent (lower segment)	25	12	10	–	5
Mean length of slopes in km	0.5	1.0-1.5	1.5-3.0	1.0-2.0.	0.5-2.5
Inclination of slopes in valley head in degrees	25-40	25-30	20-35	25-35	–
Inclination of slopes in lover seg-ment in degrees	–	12-25	23-31	–	15-30
Types of slope profiles (most frequent)	convex	convex-con-cave, convex	step-like convex	convex	convex

during low winter level fluctuates between 50-100 m (at the nivelated section upstream of Tista Bazar it measured 65 m) and during the annual high water level increase to 150-200 m. Along its bank are the sandy bars, equivalent of levees in the lowlands.

At the outlets of the tributary rivers there exists small fans. One of them, 200 m wide at the Kalijhora creek in the marginal part of the mountain was studied in detail by Froehlich *et al.*[91,123]. Its mean gradient reaches 1% at the length of 250 m. The surface and channel pattern undergo continuous transformation (Photo 36,37).

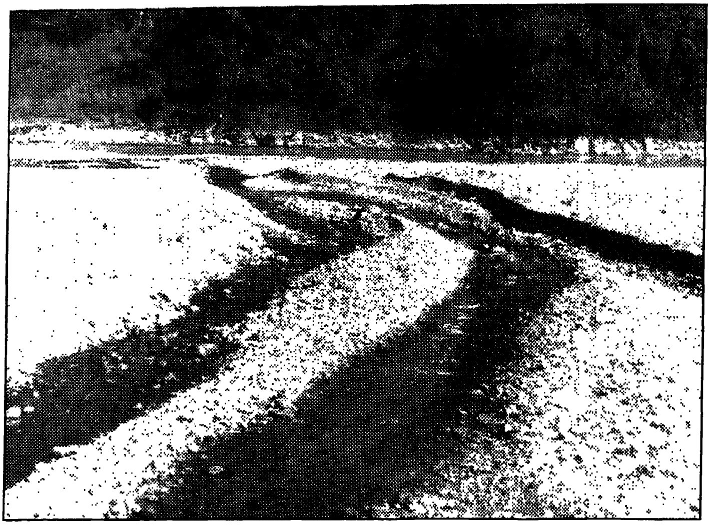


Photo 36: The channel pattern on the alluvial fan of the Kalijhora creek change after every flood (November 1986) - cf. Fig. 6.15 (by W. Froehlich)

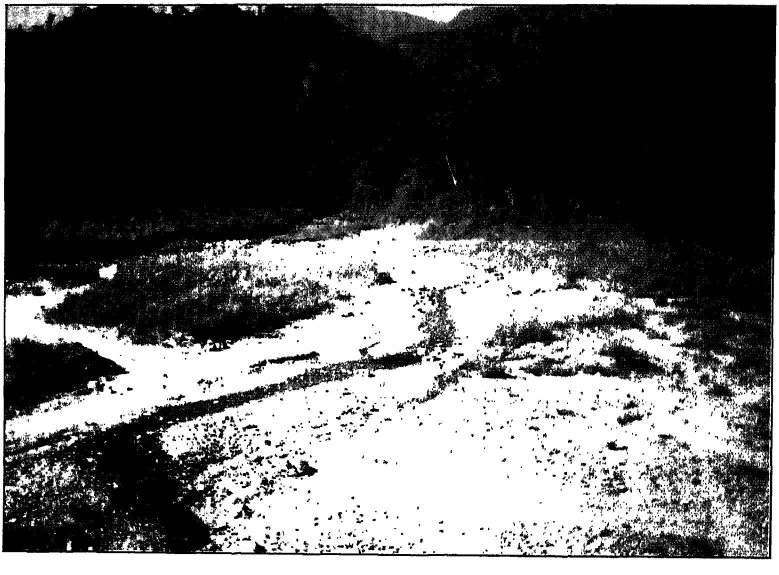


Photo 37: The upper part of the Kalijhora alluvial fan partly revegetated, upstream of the road bridge (1998) (by L. Starkel)

The length of streams dissecting only the marginal part of the Low Himalaya fluctuate between 20 and 50 km (see Table V). The gradients and channel widths in their upper reaches do not differ from the Tista tributaries of similar size of river catchments (e.g. Rangnu, Little Rangit). But closer to the mountain front their channels extend laterally, the water infiltrates into the coarse gravels. During dry season the braided channel branches dessicate totally (e.g. Lish, Chapter 5.6).

At the mountain foreland the drainage pattern is combined with the size of the Himalayan river and their morphology connected with systems of alluvial fans of various age and altitude[43,71,124]. The fragments of such higher fans are especially large at the Balasan-Mahananda interfluve near Sukna. These are accompanied by small fans of episodic creeks. The Balasan and Mahananda rivers are incised in their lower fans inclined at 1-3‰. The channel width of the Balasan also diminishes from 2 km to about 0.5 km (Fig. 6.21).

The long stripes of the Lish, Gish and Chel rivers at the mountain foreland are 3-5 km wide. About 20-40% of their total width is occupied by active channels with bars, reaching the braided channels of Tista. The Tista river itself leaving a narrow gap in the mountain front, cuts into the bedrock, divides rapidly into two in the plains and then into several branches, accompanied by active low and higher revegetated flood plains (Photo 38, Fig. 3.8, 6.22). Above them extends the floodplain to 3 m high, over which follow channel avulsions during extreme floods. At the distance of 10-20 km from the mountain front the fans of the Tista, Mahananda and Balasan rivers coalesce to form one extensive piedmont plain (Photo 39).

At the foot of the superimposed fans of smaller streams as well as at the border between two convex fan surfaces, frequently appear the springs fed by groundwater, generating the pattern of small seasonal streams.

6.2 Runoff and Suspended Sediment Load in Small Catchment (Peshok Jhora as Example)

The Peshok Jhora is the small right-side tributary of the Tista river. Its catchment area is about 12.85 km^2 and is built of intensively folded Darjeeling gneisses with intercalations of quarzites and mica shists. Steep slopes founded on the less resistant gneisses undergo quick transformation by various gravitational processes and slope wash.

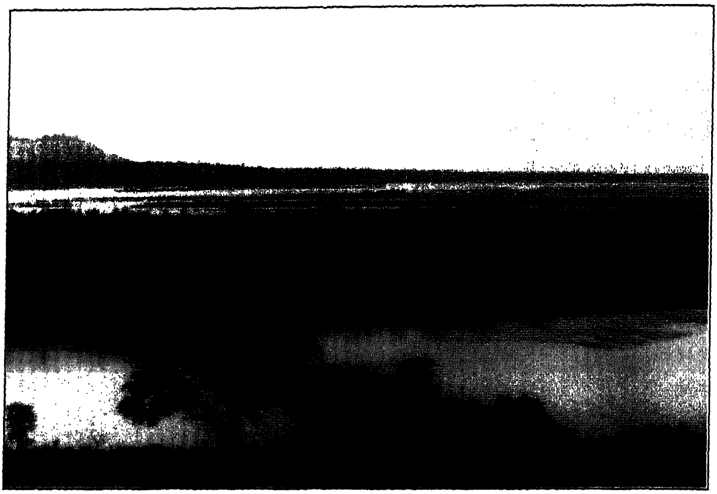


Photo 38: The root zone of great alluvial fan of Tista river during rising water level in July 1988. In the background higher fan surfaces and margin of the mountains (by W. Froehlich)

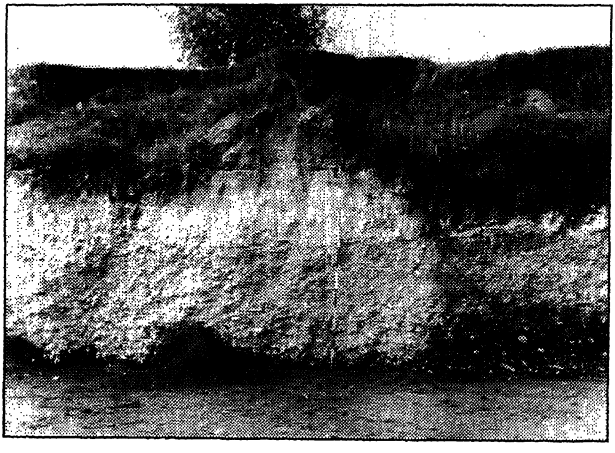
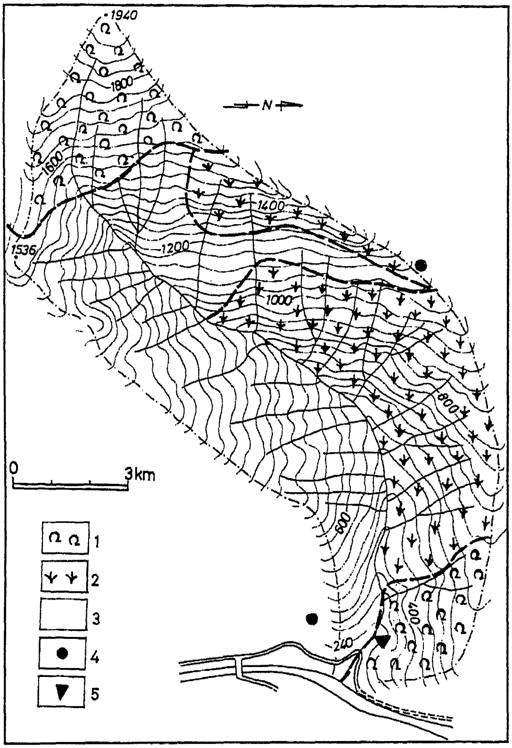


Photo 39: The floodplain of the Balasan river 4 meters high near the North Bengal University campus. Over the channel facies the sandy overbank deposits above 2 m thick (1986) (by W. Froehlich)

The catchment is exposed generally towards E-NE. Therefore, the slopes of southern aspect are getting more precipitation, then the opposite ones. The length of the catchment exceeds 7 km and the mean width 2 km (Fig. 6.1). The highest point reaches 1940 m a.s.l. and the outlet to the Tista is located at about 235 m a.s.l. The mean



1. Forest, 2. Tea gardens, 3. Other cultivated areas and under settlement, 4. Location of raingauges, 5. Hydrological station

Fig. 6.1: Land use in the Peshok Jhora catchment

gradient of the creek is passing 200‰ but in its upper course even 500‰. The inclination of convex or straight slopes fluctuate between 20° and 40°. Most of these slopes are covered by regolith of various thicknesses, the bedrock is only sporadically exposed.

The density of natural drainage measured on the topographic map 1:50 000 reaches 4.37 km km^{-2}. But their verification in the field has shown that the density is passing 10 km km^{-2} if we consider all cart-roads and artificial canals.

The channel is cut in the bedrock on its whole length. The channel debris is formed of rounded boulders and gravels with low admixture of finer material. A specific role is played by big blocks upto 3-5 m in diameter, which partially block the river flow during higher discharges and cause the deposition of finer debris in form of irregular bars, being removed later during next flood. These boulders transported downstream are piled up to several meters height in the narrowed sections. In such circumstances the coarser debris of less resistant rocks is slowly decomposed and supply the creek in fine fractions. A substantial role in the delivery of debris play various types of landslides.

The local climatic condition does not differ from regional pattern. The partly transversal position of catchment in relation to advection from the south causes contrast in the rainfall pattern between opposite slopes. The mean annual rainfall (1989-1992) at the station elevated 330 m a.s.l. reaches 2251 mm and at Peshok Tea Garden (1942-1988) at the station elevated 750 m a.s.l reaches 1882 mm. (Fig. 4.1).

Natural vegetation consist mainly of Sal (*Shorea robusta*) which is more noticable in the northern aspect on deeper soils. On the whole Sal is of a rather poor quality. Dry mixed forests are mainly found on the ridges and spurs on the southern aspect. Patches of wet mixed forest are found in central pockets of valleys and mostly on the northern aspect. Except very steep slopes most of the government owned forests has now been converted into the teak (*Tectona grandis*) plantation.

The total land use structure is as follows: tea gardens - 367 ha (29%), agricultural land - 367 ha (29%), forest - 488 ha (38%), and roads, buildings etc. - 63 ha (4%).

About 29% of gently and steeper terraced slopes are occupied by tea plantations. The cultivated fields and gardens have the shape of terraces mainly 4-5 m wide, but sometime only 1-2 m. Only on the flattened ridges the fields may reach 100-300 m^2. Most of slope fields are irrigated by a network of small canals and dams, which totally transformed the water circulation on slopes.

The Peshok TE and Lopchu TE occupy the western and northern parts of the catchment. Their condition is not good, many parts are disturbed by scars after debris flows. Similar area is under agriculture, including cultivated terraced fields (the real arable lands cover only 24 ha), orange gardens, cottages etc. Among cultivated plants dominate rice, buckwheat, potatoes and various vegetables. In the catchment about 1000 persons are living and are breeding about 500 cows, goats and sheep. These animals are important erosional factor in the forests.

For this catchment, the evaluation of potential erosion has been prepared following the Indian official standards. In the AGRI-509 report[125] the following five categories have been distinguished:

A –367 ha (28% of total area) - steep slopes, partly forested (under terraced cultivation 1-3 %) with outcropping bedrock, gullies and very intensive erosional processes.

D –150 ha (12%) - steep slopes, medium to dense forests, frequent gullies, sporadic landslides, intensive erosional processes.

E –100 ha (8%) - patches of shrubs and grasses, bamboo plantations, steep slopes with frequent landsliding and creeping, medium to intensive erosional processes.

F –150 ha (12%) - steep terraced slopes with sandy and silty soils, temperate erosional processes.

H –151 ha (12%) - shrubs and meadows over landslides, distinct erosional processes.

M –367 ha (28%) - narrow terraced fields with tea plantations, well drained, deep soil, weak erosional processes.

Although this classification does not include quantitative parameters of soil erosion but it is of common use (Sarkar[75] Chapter 5.6). The two main criteria of this classification are slope gradient and vegetation cover. The well cultivated tea gardens are classified as the areas of very weak erosion. In group M cultivated terraced fields, where during normal rainy season the erosion may be at most moderate, but during extreme rainfalls the saturated soil undergoes liquifaction and flows down are also included. Using equation prefered by FAO and UNEP the maximal erosion calculated for the upper reach of the Mahananda basin should reach 10000 t ha^{-1} eg. 600 mm yr^{-1},[75]. The highest measured value does not pass 80 t $ha^{-1}yr^{-1}$ eg. 1% of that maximal value.

During the period 1988-1992 there existed a hydrological gauging station at the outlet of the Peshok Jhora to the Tista river, maintained by the Indian Survey for protection of soils and forest areas. Every morning the rainfall total, water stages (and calculated discharges) and sediment concentration (by drying-weight method) was measured there. The collected records were not uniform. Especially care should be taken to consider the single values taken for the highest discharges. The real maxima after heavy downpours in the evening hours were probably not measured. Therefore mean monthly values were used in calculations after correcting errors and missing some uncertain records. So collected data were supplemented by "All India Soil ..."[125] and then the runoff and sediment load calculated therefrom.

During 1989-1992 the annual rainfall totals at the lower station fluctuated between 1958 and 2408 mm and in July reached 500-700 mm (Fig. 6.2). At other station on the watershed at Peshok TE the rainfall in previous period 1942-1988 fluctuated between 1369 and 2645 mm and were generally lower.

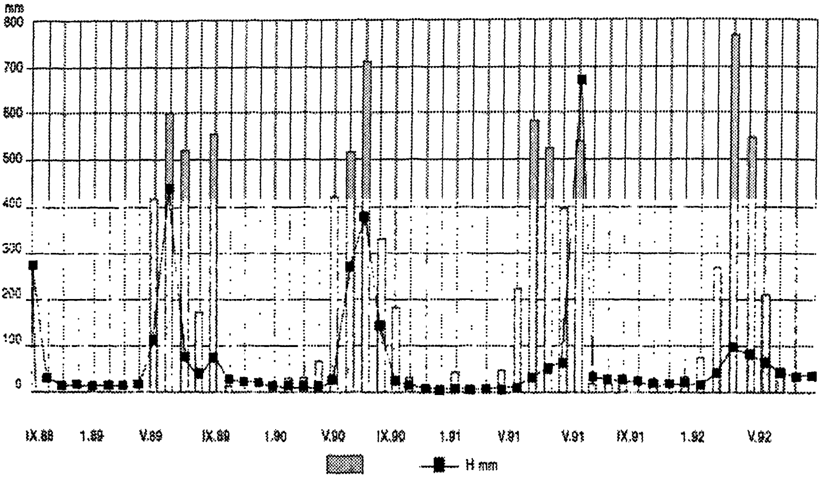


Fig. 6.2: Precipitation totals and runoff in Peshok Jhora (VI.1988-XII.1992)

The mean annual discharge was 0.338 m^3s^{-1} and specific runoff 30.2 l s^{-1} km^{-2}. The total annual runoff was calculated to be 828 mm eg. 38% of total rainfall (Fig. 6.2). The mean concentration of suspended load was calculated to be 0.1906 g l^{-1} but the highest measured 12.64 g l^{-1} and the highest monthly value at 3.33 g l^{-1}. From these data the mean annual suspended load at 7440 t and denudation rate 0.4135 mm yr^{-1} were calculated. The denudation from 1 km^2 will be 579 t yr^{-1} (Fig. 6.3).

The hydrological regime of the Peshok Jhora reflects the seasonality of the monsoon climate. From October till April the suspended load is negligible. The annual totals depend on the summer floods. Between

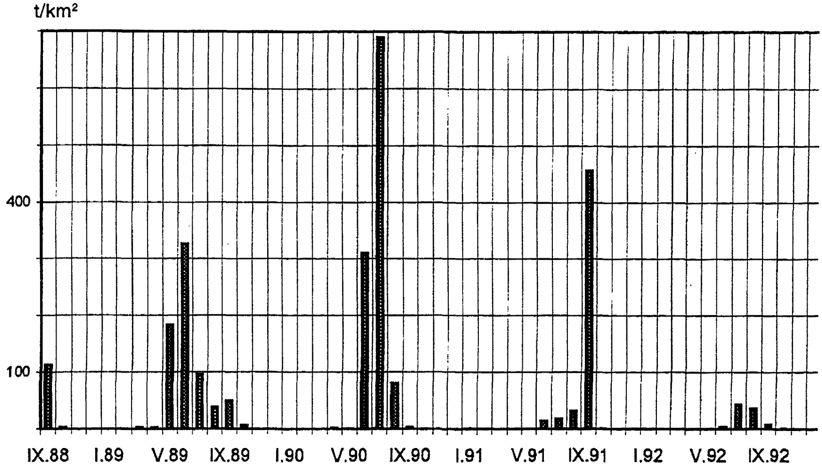


Fig. 6.3: Rate of denudation in Peshok Jhora VI.1988-XII.1992

3 and 9 July 1990 took place a typical clustering of rainy days (30-80 mm every day) with a total rainfall of 384 mm (Fig. 6.4). The runoff response was very rapid and reached 152 mm (runoff coefficient 40%), the measured discharges reached 6 $m^3 s^{-1}$. During 7 days the suspended load passed 5100 t and measured concentration reached 5.6 $g\ l^{-1}$ (Fig. 6.5). During the following flood at 18-19 July after rainfall of 133 mm the calculated runoff reached 50 mm and sediment load 2400 t (highest concentration 4.2 $g\ l^{-1}$). In July the suspended load reached 65% of the total annual value. Next year in September at the end of the rainy season the 8 day suspended load covered 85% of the total annual value. This means that high sediment load is connected with the consecutive rainy days. The lack of high concentration after single rains may be is caused by missing observations of highest runoff as the measurements were taken in the morning hours and local downpours were mainly concentrated during late afternoon or evening.

The correlation between runoff and sediment load is difficult to discribe by one formula due to great variability of both parameters and insufficient frequency of records. Nevertheless there is a distinct increase in suspended sediment concentration during consecutive rainy days. During the single rain of 50-100 mm mainly lower concentrations were recorded than after consecutive rains.

The denudation rate of 5.79 t $ha^{-1}yr^{-1}$ for the Peshok Jhora catchment belong to lower values reported from the Darjeeling Himalaya. This is due to still lesser human impact and preservation

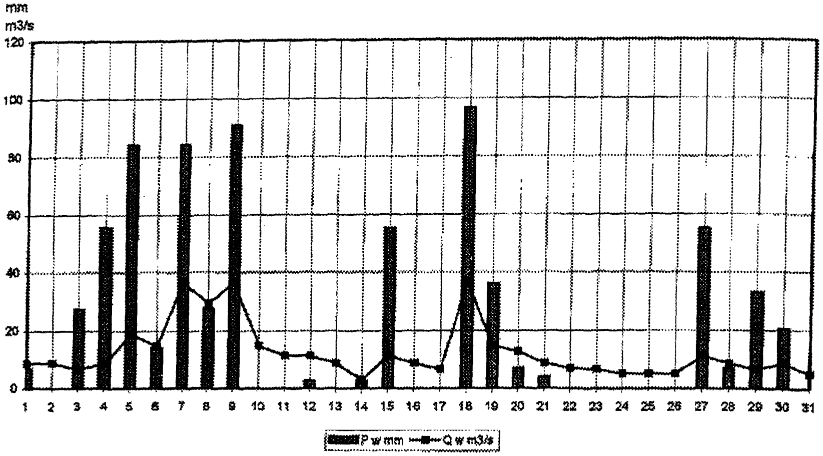


Fig. 6.4: Precipitation totals and runoff in Peshok Jhora in July 1990

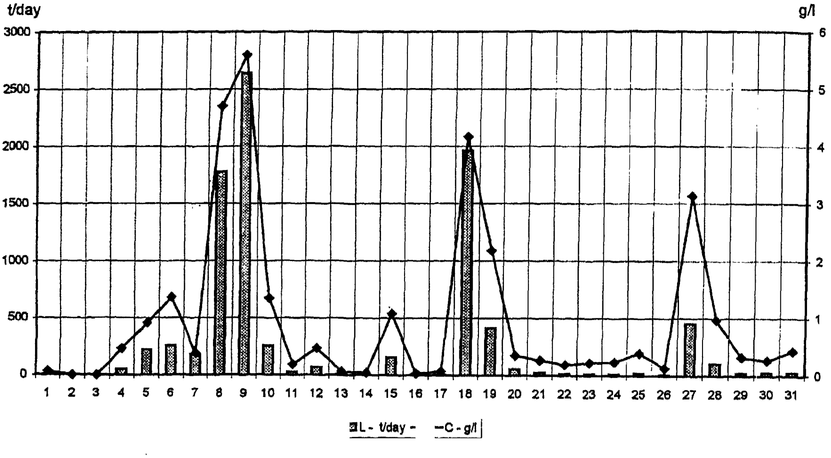


Fig. 6.5: Suspended load and its concentration in Peshok Jhora in July 1990

of natural forest in patches. Similar or higher values are reported[75] from the Mahananda river basins in Champasari, where in 1985-1987 the mean suspended load was 1200 t km^{-2} and maximal suspended load concentration 1.24 g l^{-1}. In the Balasan basin in years 1990-1993 mean suspended load was much higher 2980 t km^{-2}. In 1991 due to an extreme flood the denudation rate calculated on the basis of suspended sediment load was 6610 t km^{-2} (denudation rate of 9.2 mm yr^{-1}).

The denudation rate registered in the Peshok Jhora catchment seems to be typical for the environment of small watersheds in the Darjeeling Himalaya still with higher forest percentage than the average. These values are characteristic only for the normal summer precipitations. During catastrophic rainfalls the denudation rate in the Peshok Jhora and other catchments was probably higher by one or two orders, what has been registered by numerous landslips and debris flows after October 1968[1] and is indicated by the presence of big boulders transported in the channel of the Peshok Jhora and scattered over the steep alluvial fan sloping to the Tista river (Photo 35). During several visits of this fan between 1984 and 1995 changes of its surface and new boulders, showing the supply of fresh material from the upper catchment were observed.

The data on the sediment load in the Himalayan river catchments were mainly collected during one or several years. The greatest collection related mainly to Nepalese part contains the monograph by JB Ries[126]. The lowest value of 200 t $km^{-2} yr^{-1}$ was recorded in the forested Surma Khola (catchment of 5.7 km^2) and the highest 7000-8000 t $km^{-2} yr^{-1}$ in Tamur basin of 6000 km^2 in eastern Nepal. Near Kathmandu in the catchments of 12-15 km^2 the annual sediment load fluctuated between 1300 and 4600 t km^{-2} and is difficult to find the relation to land use and percent of deforestation[126]. T Hofer (1993) even call in question the direct impact of the forest cover on the runoff regime in the Indus catchment basin.

6.3 Generation of Flood and Sediment Load

The rivers of the Darjeeling Himalaya are characterised by rainy - ground-water regime. Only the transit river Tista is also supplied by snow and glacial melt-waters from the high Sikkim Himalaya, which is reflected in the slow rise of river discharge before the start of summer monsoon (Fig. 6.6).

The common feature of the Tista valley and all other valleys of young rising mountains is the direct contact of steep slopes and river channels. A rapid water and sediment delivery to the channels has great importance for the mechanism of flood generation and sediment load. A quick formation of flood waves is reflected in steep and narrow hydrograms (Fig. 6.7) and rapid rise of suspended sediment concentration during the rising water stage.

The concentration of rainfalls during summer monsoon causes higher river discharges from May till October. This is a period of water surplus in the runoff balance, especially distinct in the years with

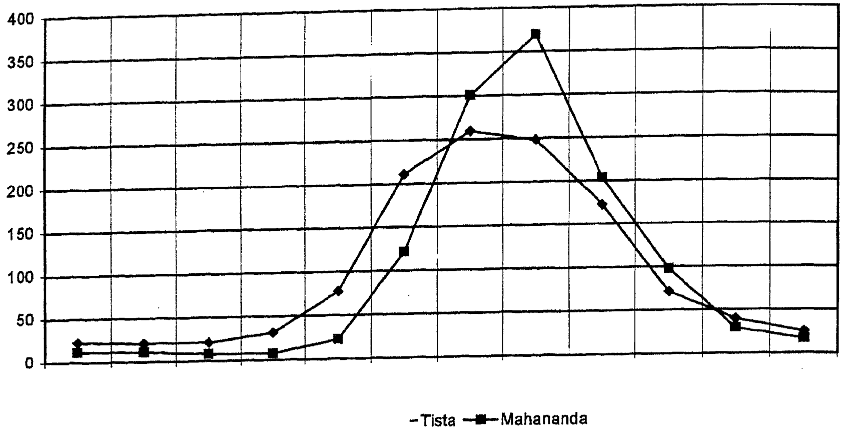
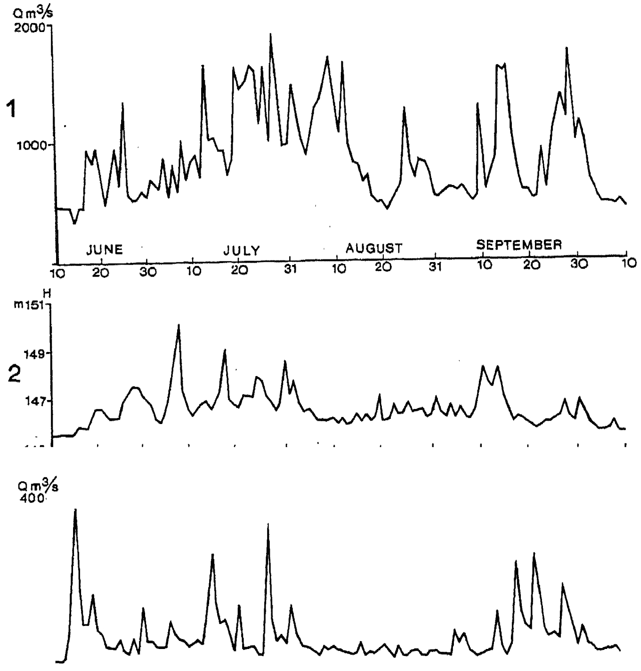


Fig. 6.6: Monthy Parde coefficient (Qm/Qyr X 100) for Tista and Mahananda rivers



1. Discharge of Tista river in 1970 at Coronation Bridge (after Dey[127]), 2. Water stages of Tista in 1986 at Coronation Bridge (after Dey[127]), 3. Discharges of Balasan river in 1991 at Siliguri

Fig. 6.7: Examples of annual course of river discharge and water level

extreme continuous rains and floods[1,66,127]. On the contrary from November till early May is a period of low water stages.

The catchment of the Tista river and its main tributary the Great Rangit forms the main fluvial system in the Sikkim Himalaya. In the mountainous part the run-off and sediment load are registered only at two gauging stations in Tista Bazar and Sevoke Bridge. At this reach the river channel undergoes incision in the alluvial sediments and bedrock[66]. The next gauging stations are located in the mountain foreland in the typical course of braided channel system (Jaipalguri in India and Kelly in Bangladesh).

Due to the sandy substratum the river channels change their hydrodynamic conditions also during low waters stages. Therefore all hydrometric records are having distinct errors, and these make the situation very difficult for comparing data of longer duration. The longer multiannual comparison is also restricted by the confined character of records on water resources, which is connected with irrigation systems in the border zone with Bangladesh.

The other gauging stations on several rivers at the direct foreland of the Darjeeling Himalaya are also located on unstable channels of aggrading alluvial fans (Mahananda at Champasari, Balasan at Siliguri, Lish and Gish at Bagrakot). Efficiency of sedimentation processes compels to change the calculated discharge curve very frequently. The mechanism of discharge is also complicated by a very high infiltration in the coarse alluvia and by subsurface drainage[1,49,63]. Detail measurements of runoff and sediment load were carried only in several small catchments of the Kurseong Forest Division[104].

The complex distribution of rainfalls in time and space is reflected in great diversity of discharges[76,128]. The initial rains of the summer monsoon are consumed through evaporation and evapotranspiration and stored in the soil[40]. A distinct rise of water stages and discharges follows after a month's delay when the daily rains cause the full saturation of the soil profile. Between June and early October higher rainfall totals and intensity cause several times the passing of bankfull discharges. The extreme floods show a frequency of 30-50 years[66]. The highest mean monthly discharges are registered in June, July or August and any shift depends on rainfall pattern[129]. After the end of summer monsoon the rivers are fed only by the ground waters and from November the slow falling water stages is observed, reaching its lowest value between December and April. A good example of annual course of water flows from hill springs in southern Sikkim is presented by RN Rai *et al.*,[130].

The heavy summer rains continuing for several days cause flood waves characterised by rapid rise, short culmination and falling water stages. The highest annual specific run off in larger catchments fluctuate between 1.5 to 5 $m^3 s^{-1} km^{-2}$ [66]. Such event is well visible in the smaller catchments (cf. Chapter 6.2.). In July 1988 after a heavy downpour of at least 80 mm in 30 minutes a high discharge of debris flow several metres long, followed by rapid recession(measured at Kalijhora) was observed at the confluence of the Kalijhora with the Tista river. A few hours later the creek returned to is normal low discharge.

This rapidity of flood generation is connected not only with high rain intensity but also with full saturation of soil profile and high gradients of the bedrock surface. The accelerated subsurface run off is controlled by a high permeability of regolith and high drainage density.

The repetition of flood waves every year reaching or passing the bankfull discharge is reflected in the mountains in the channel cross-sections stabilised by log horizons of boulders and gravels. Their geometry may be changed only during extreme floods[1]. On the contrary the shallow unstable channels cut in sandy alluvial deposits change their character after every higher water level (Photo 40, 41). This process is accompanied by a relatively high sedimentation rate of the overbank deposits and a continuous supply of bedload of sandy fraction also during the low water stages[26].

In the Tista and the Great Rangit rivers the season of high discharges continues from May till October when over the meltwaters from the high Himalaya is superimposed the subsurface run off of rainy origin. The ground water component of total run off does not exceed 25%. During dry season the river discharge is very stable and at Tista Bazar cross-section it drops below 100 $m^3 s^{-1}$. At that time the specific run off is droping to 10 $l\ s^{-1} km^2$. In July the highest mean specific runoff exceeds 200 $l\ s^{-1} km^2$. Following available data[158], the mean annual discharge of Tista is calculated at 581 $m^3 s^{-1}$ (spec. runoff 85 $l\ s^{-1} km^2$) and highest annual discharges reach 4000-5000 $m^3\ s^{-1}$.

The highest calculated Tista discharge at Tista Bazar during the 1968 flood was of the order 18 500 $m^3 s^{-1}$,[66] and on the foreland in Jalpaiguri 19 800 $m^3 s^{-1}$. In the last 100 years the floods of that order were registered also in 1899 and 1950 as well earlier in 1787.[1,131] The frequency of such events is one in 30-50 years.

The flow velocity of the Tista river measured in November 1989 near outlet of the Kalijhora stream during low water level was about 2 $m s^{-1}$. During the October 1968 flood[95] in the mountain reach the velocity reached 8-13.5 $m s^{-1}$ and in the foreland never exceeded 4 $m s^{-1}$.

During annual floods the water level of the Tista at Tista Bazar reaches up to 6-7 meters, which is underlined by the absence of vegetation on steep valley sides. The 5-10 years floods exceed 10 meters and during the 1968 event water exceeded 26 meters above level before the flood[66,95]. In the multiannual course the lowest and the highest water levels are regulated by tendency to erosion or aggradation in the channel bottom. In the 1970's (1973-1983) the mean incision in Tista Bazar was of the order of 0.1 m yr^{-1} and at Sevoke bridge, downstream, over 0.3 m yr^{-1} (cf. Fig. 6.18).

The regime of the Mahananda and the Balasan rivers draining the marginal part of mountains distinctly differs from the Tista, supplied by the meltwaters (Figs. 6.8 and 6.9). Here the higher discharges end in September or in October. During the rainy season the course of discharges follows the rainfall pattern. In the case of the Balasan river the peak discharge in 1991 exceeded 900 $m^3 s^{-1}$ and during the same event the Mahananda reached 758 $m^3 s^{-1}$ [68]. A low storage capacity during high intensity rain causes every year the formation of short steep water discharge rises from the level of 600-700 m^3 in the Tista and 20-50 $m^3 s^{-1}$ in the Balasan river up to 1500-3000 $m^3 s^{-1}$ and 300-400 $m^3 s^{-1}$ respectively. During every rainy season in the Balasan about four high water stages are registered but their number fluctuates between 1 and 7. The Tista river with the greater basin registers up to 10 floods and more. A special feature of this regime is appearance of extreme discharges at the end of a rainy season, when the substratum is fully saturated. This type may be illustrated by the great flood of October 1968, as well as by the smaller one of September 1991, when the highest discharge was shifted by 1-2 days in relation to the rainfall, which might by partly explained by specific method of registration.

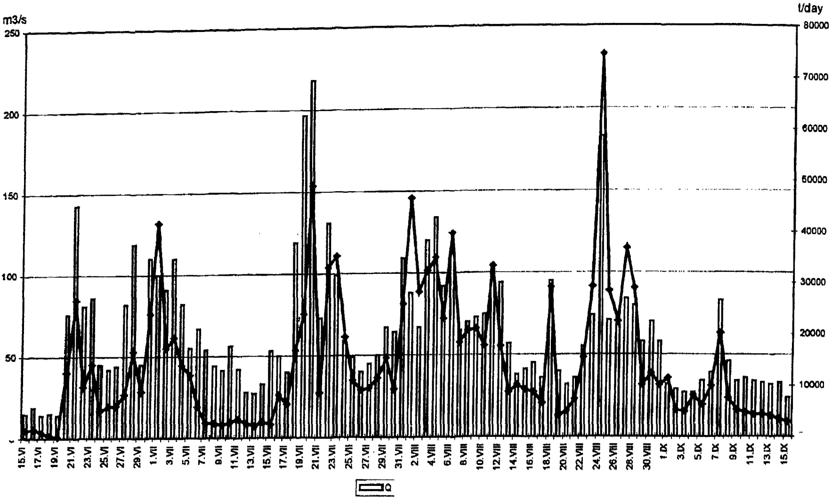


Fig. 6.8: Discharges and suspended load of the Mahananda river at Siliguri in 1990 15 June - 15 September

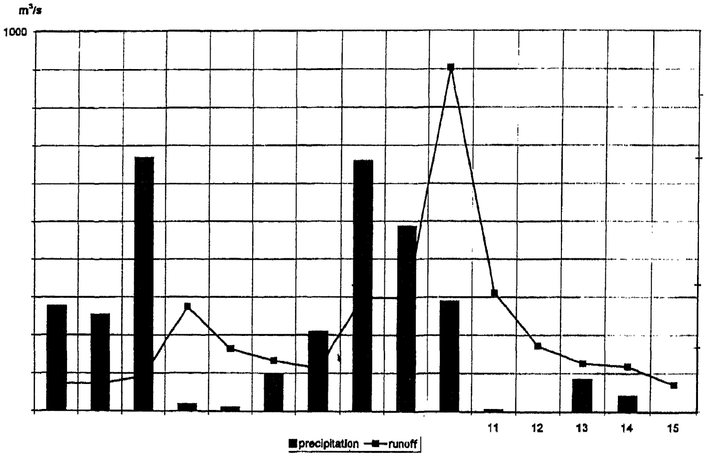


Fig. 6.9: Discharge of Balasan river at Siliguri and precipitation at Castelton T.E., 1-15 September 1991

Fluctuations of water stages are controlled by the shape of channels, in the deep Tista valley being narrow and therefore sinking over the whole valley floor. In the mountain foreland over the floodplains the water rises are limited by embankments and irrigation systems.

The deep subsurface run off, reaching about 20% of the total run off, control the river supply during dry season. At that time the specific run off fall down even to several l s^{-1} km^2. In drier years in some marginal mountain catchment the surface runoff stops totally. Its rapid decrease in all catchments at the mountain front is connected with quick infiltration of water in the thick alluvial fans. This is especially well observed at the outlet of Lish, Gish and Chel rivers from the mountains[1,49,61,63].

The direct contact of active sliding slopes with the river channels causes a high efficiency of sediment delivery and great diversity of sediment sources (Photo 4, 30, 42). To ascertain the main sources of suspended sediment load the 'fingerprint' sediment source method was used by introduction ^{137}Cs as natural tracer[132, 133]. The studies were

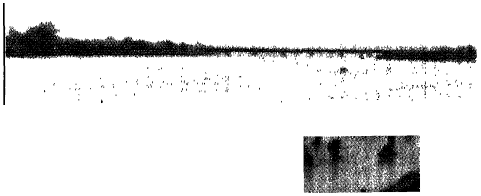


Photo 40: Exploitation of gravels in the Balasan river during higher water level in July 1988 (by W. Froehlich)

Photo 41: The Mahananda river near Gulma at the mountain front during low water level (winter 1987) (by S. Sarkar)

Photo 42: The landslide on the Tista valley side (1989) (by L. Starkel) carried in the Rangnu river catchment at Bannockburn TE and Ging TE. It was stated that the fraction > 0.063 mm carried as suspended load is characterised by very low concentration of ^{137}Cs, which indicate that the areas of contemporaneous intensive erosion are the main source of suspended sediment. Similar low concentration was registered in a silty fraction over fresh, not revegetated colluvial sediments. These landslide or earth flow are now mainly dissected and drained to stream channels[134].

Much higher concentration of ^{137}Cs was found on the ground surfaces in the tea gardens and forests, where the movement of suspended sediment is associated with the dispersed overland flow. Such distribution of concentration of ^{137}Cs indicate, that during annual floods the main source of suspended load are the eroded colluvial tongues of landslides and earth-flows. It should be underlined that low concentration of ^{137}Cs in suspended sediment supports the statement on a less importance of dispersed slope wash as well as of overland flow in the creation of runoff in the Darjeeling Himalaya.

The grain size composition of soils it characterised by the dominance of sandy fractions and relatively low content of clay below 10%. Such composition restricts the potential delivery of suspended matter by overland flow. During summer rainy season the concentration of the suspended load is closely related to the course of rains and river discharges. The lowest concentrations of 1-10 mg l^{-1} were registered during low water stages from November till April as well as during longer inter-flood breaks in summer. The Tista river in the summer season carries mainly clayey and coloidal fractions, reflected in the milky-white colour of water. Data on the suspened sediment concentration during extreme floods are not available.

In July 1988 during rising flood wave caused by a daily rainfall reaching 115 mm in the river channels of the Balasan, the Mahananda as well as the Tista river at the mountain foreland relatively low concentrations of suspended sediment between 148-289 mg l^{-1} were registered. Much higher values were recorded in the small catchments during high intensity rains. These are connected with the efficiency of sediment delivery by linear erosion and mass movement. Locally the thresholds of hyperconcentrated flows and debris flows may be passed, causing substantial transformations in the channel geometry and sediment supply by mass movement[1]. In the Peshok Jhora between 1988 and 1992 the highest recorded concentration of suspended sediment has reached 12,6 $g \cdot l^{-1}$ (cf. Chapter 6.2).

In the annual course the suspended load follows a general course of river discharge. About 70% of the annual suspended load is carried during higher discharges in July and August. The remaining 30% is transported during the other 4 months between May and October. The leading role is played by extreme floods. The two-day flood in the Balasan river in 1991 delivered 64% of the total annual suspended load.

In the regional scale the Sikkim Himalaya are characterised by very high denudation rates reaching 500-1000 t $km^{-2}\ yr^{-1}$ calculated on the base of suspended load[135,136]. In the above mentioned Peshok Jhora catchment the mean annual sediment yield (1988-1992) reached 7440 t eg. 579 t $km^{-2}\ yr^{-1}$ and the denudation rate of 0.4 mm yr^{-1}. This relatively low values are connected with land use structure (still 38% of area under forest). On the basis of suspended load Sarkar[67,76] calculated denudation rate in the upper Mahananda basin (1983-1993) as to be the order of 5000 $m^3\ km^{-2}$ eg. about 10 mm yr^{-1}. Similar values of about 8 mm yr^{-1} are calculated for neighbouring basin of the Balasan.

The high water velocities during floods restrict the deposition on the banks of flood plains in the mountains, where along the Tista prevail the sandy deposits with silts deposited on the point bar sides. On the mountain foreland sandy fractions are being transported as the bedload[26,137,138]. This type of transport is common also during low water stages[139, 140].

During extreme floods the hyperconcentrated flows[141] are carrying heavy bedload including at the mountain margin boulders (0.5-1 m in diameter and more). These are spread in the channels of the Balasan, the Mahananda and other river up to several kilometers from the mountain front and taken immediately for construction purposes.

6.4 Channel Formation During the Extreme Flood of 1968

In December 1968 (as well as in November) the changes in the river channel, changes and new sedimentation, created by the flood on 4-5 October were closely observed. All erosional and depositional forms were well preserved as there were no appreciable rainfalls after that event.[1] The scale of transformation differs depending on the size of the catchment, length and gradient of river and on the height of flood wave.

River Channels of Various Orders

In the valley heads and on the dissected slopes inclined to 10-50% or more, debris flows caused in several cases the scouring in the older colluvium or in the bedrock. Many valley sides in deforested areas were undermined and slump or slides created. In the forested areas (e.g. Little Rangit Block) mainly gravel fraction was carried by water. In the narrow gullies big blocks were plugged locking in the incision (Photo 13).

In the 2nd to 4th order streams, draining catchments of 5-20 km^2, the transformation was more pronounced. In Posam creek near the tea factory at Pussimbing TE with the mean gradient of 15% there was transported a debris bounded flow with blocks 2-6 m in diameter which downstream turned to hyperconcentrated flow with imbricated broken blocks on the top (Photo 43, 44). In this section, incision started reaching upto a depth of 7 m at the end of this flood (Fig. 6.12). But earlier, the debris covered the older valley floor to a width of 80 m and upto an elevation of 8-9 m.

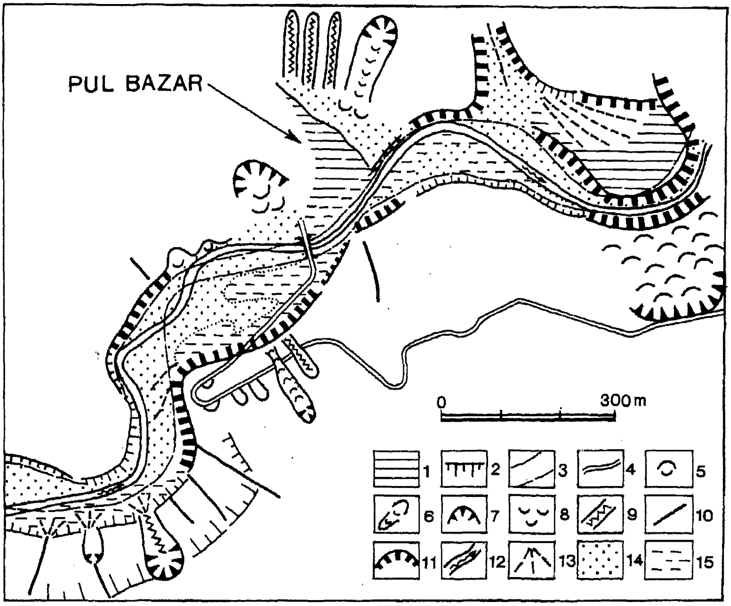
Photo 43: The floor of the Posam creek valley transformed in October 1968, filled with boulders. On the left the outlet of landslide (Photo 16), supplying the debris flow (December 1968) (by L. Starkel)

Photo 44: Debris flow boulders reworked by hyperconcentrated flow in Posam creek (December 1968) (by L. Starkel)

In the Pachim creek (Ringtong TE) with lower gradient (10%) only the blocks upto a diameter of 2 m were removed by the flowing water. The wide terrace of 8 m height was built up by fans and debris tongues coming from the slopes.

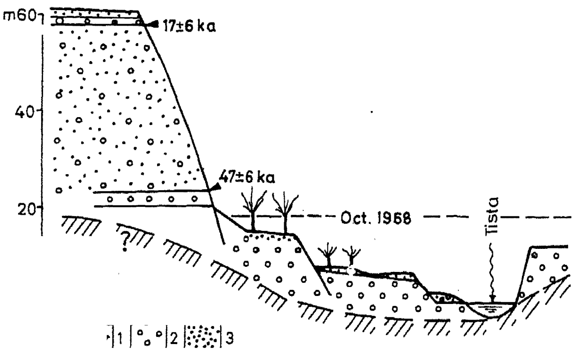
In the larger Rangnu creek (33 km^2) near Bannockburn TE, the whole valley floor having a width of 100 m was first covered by debris upto a diameter 2 m and then slightly dissected (Photo 30).

In the Little Rangit valley near Pul-Bazar the former river-bed was 25-50 m wide while the creek is only 5-8 m wide. On the valley floor there were the rice fields (Fig. 6.10). During the October event the water level was raised by at least 10 m, the aggradation and lateral erosion (to 50 m) caused the widening of the channel upto about 80-200 m (Photo 45). The newly built bridge (13 m high) was burried



1-4 Older preserved forms: 1. Terrace and fan surfaces, 2. Erosional scarps, 3. Former extend of river channel, 4. Old road and bridge, 5. Small slumps, 6. Mudflows and slumps, 7. Landslide scarps, 8. Landslide tongues, 9. Tracks of debris flows, 10. New gullies, 11. New undercutting by lateral erosion, 12. New river channel, 13. New alluvial fan, 14. Channel bars build of boulders and gravels, 15. Overbank deposition (gravels and sands)

Fig. 6.10: Geomorphological map of fragment of Little Rangit valley near Pul Bazar in 1968 (after Starkel[1])



1. Bedrock, 2. Channel coarse facies, 3. Overbank sandy facies

Fig. 6.11: Schematic cross-section of Tista valley near outlet of Kalijhora creek with late Pleistocene terrace dated by TL method, extend of 1968 flood and two flood-plain levels: from 1968 and annual

and behind it the aggradation of boulders of 2-3 m in diameter took place upto a height of 10 m (Photo 46). The hyperconcentrated flow transported blocks of 8-12 m in size. During the low water, finer gravel bars were deposited. In some sections the sequence of changes in the stream power caused the aggradation starting from the gravels at the bottom to 1-2 m blocks and again to 0.2-0.5 m and finer on the top (Photo 47).

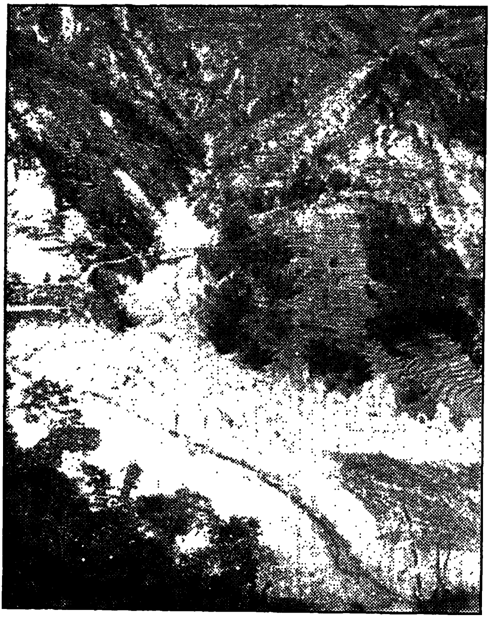


Photo 45: Agradation in the valley floor of the Little Rangit and transformation of deforested slopes by various mass movements in October 1968 (December 1968) (by L. Starkel)

These preliminary observations formed the background for calculations of water velocity

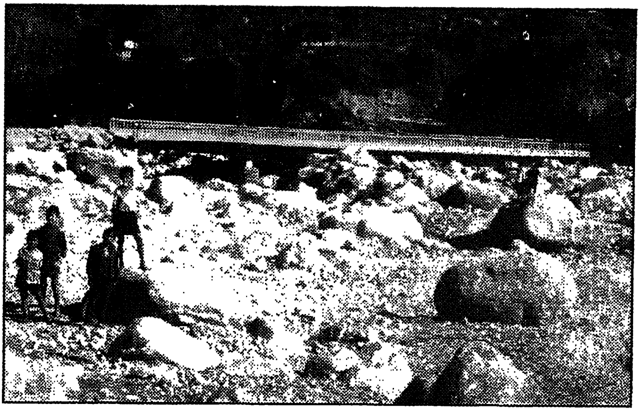


Photo 46: Partly burried bridge formerly 11 m high over the Little Rangit river in Pul-Bazar (December 1968) (by L. Starkel)

Photo 47: Deposits of the October 1968 event in the Little Rangit valley showing the alteration of coarser and finer debris beds (1984) (by W. Froehlich)

and river discharge. In the first paper[1] the size of boulders and river gradient were used to calculate the mean velocity and the highest discharge as well as the specific run-off. In case of the Posam creek the expected velocity was about 13 m s^{-1} and the specific run-off 156 $m^3 s^{-1}$. For Little Rangit a maximum discharge at 5625 m^3s^{-1}, and specific run-off at 75 m^3s^{-1} was calculated. These values were much too high and overestimated at least several times the highest rainfall intensity (about 1 mm s^{-1}). That time the hyperconcentrated flow[141] was not taken into consideration. During the full saturation the specific runoff in the mountains may reach 15 m^3. In 1987 we assumed that considering the possibility of an episodic retention of water in the ground and the occurrence of occasional barrages by debris flows and rockfalls, the specific run-off in smaller catchments could pass the rainfall intensity by 3-5 times[66].

In case of the Pachim creek (Ringtong T.E.) where debris flows were not recorded in the main river channel, the calculation of the discharge and specific run-off based on the size of boulders seems to be not overestimated (14.3 m^3 s^{-1} cf. Starkel)[1].

Flood in the Tista Valley

The measured high water level in the evening of the 4 October 1968 was 18-20 m higher than the low water level in December. At Tista Bazar the iron concrete Anderson Bridge was swept away. Their elements were transported downstream by tens and hundreds of meters. Both channel sides were undercut, the vegetation eroded and big landslides were mobilised[1, 92] (Photos 48, 49).

Photo 48: Landslide in Tista Bazar on the right bank of river. On the opposite side of Tista the remains of totally damaged Anderson bridge (December 1968) (by L. Starkel)

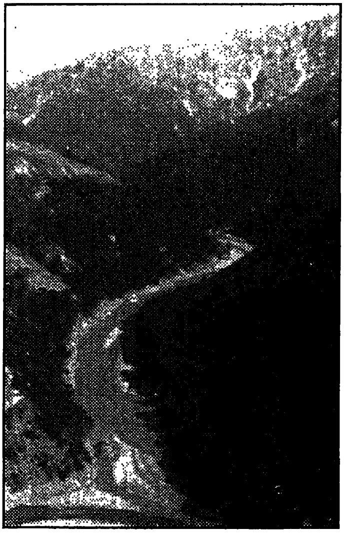


Photo 49: The junction of the Tista river with Grēat Rangit after October flood. Banks undercut to about 20 meters (December 1968) (by L. Starkel)

On the meander curves the point bars were deposited but there were much more visible signs of erosion[1]. More detailed examination in 1984 has shown that there exist segments of channel armoured by big boulders which suggest the aggradation during 1968 flood[66].

Reconstruction of water level has clarified this picture.[66,92] Before the flood (30.09.1968) the water level of the Tista at Tista Bazar was 201.8 m a.s.l. On the 4th October early morning it passed 206 m and at 11 p.m. reached 228.6 m (rise by 26.8 m). On 1st January,1969 the low water level was 207 m a.s.l. This means that the channel floor had risen by 5-6 m (cf. Fig. 6.18 and 6.11).

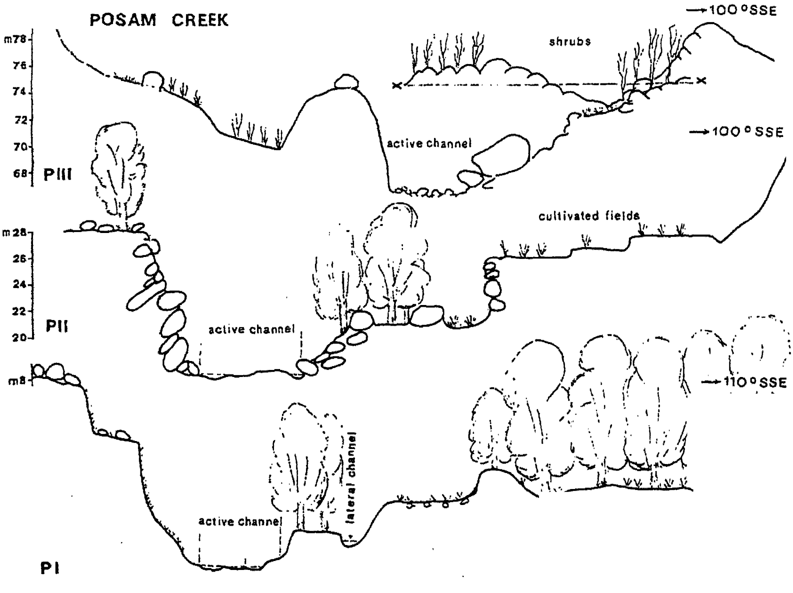
In the paper by Starkel[1] the maximum discharge of the Tista was estimated to be 27500 $m^3 s^{-1}$ at Anderson bridge assuming the stream velocity to be 5.5 $m s^{-1}$ (after information in the newspaper). But after actually surveying the channel profile 700 m upstream, the highest discharge was estimated at only 18150 $m^3 s^{-1}$ [66]. This corresponds well with the discharge reported for the Jalpaiguri section in the plains (19800 $m^3 s^{-1}$) where the Tista entered the flood plain with the subsequent change in its course. Sanyal[95] describe much higher stream velocities from 4 $m s^{-1}$ near Jalpaiguri and 8.1 $m s^{-1}$ at the outlet from the mountains upto 13.5 $m s^{-1}$ in Sikkim. This last value correspond with the values estimated for the smaller streams[1].

The 1968 event with the recurrence interval of 30-40 years has shown that due to the high rainfall intensity during several hours a simultaneous transformation of slopes and river channels took place. Therefore the flood wave 10-20 m high supplied with debris flows, slides, rock-falls acted as hyperconcentrated flow carrying large boulders and trees which additionally dammed the rivers. In the upper courses the downcutting prevailed but downstream at the channel gradient below 50‰ the accumulation of coarse boulders started to dominate. In the longitudinal profile of the Tista and other rivers the tendency of changes in vertical position of the channel bottom depended on the delivery of coarse materials from the sides (slopes and tributaries). In the Balasan valley the aggradation shifted several kilometers upstream due to the formation of a great colluvial fan starting at the outlet of the Ambootia landslide valley.

6.5 Channel Changes in Mountain Valleys of Various Order

During several visits in the Eighties and early Nineties the repeated measurements and observations were made and data on the variations of the water level of various rivers were gathered as well. Among these were the Posam creek, the Jhepikhola and Rangnu creeks, short sections of the Little Rangit and the Balasan river, the junction of the Great Rangit with the Tista river, as well as the Tista itself near Peshok Jhora, at Anderson Bridge, near the junction with the Kalijhora and at Sevoke bridge (cf. Fig. 2.1).

The Posam creek channel which cut upto 7 m in the debris flow blocks at the end of the 1968 event, was studied for about 4-4.5 km from its source. In February 1984 the whole valley floor with big boulders and the incised channel were revegetated by trees (10 m high) and shrubs and the channel width declined from 20-80 m to less than 10 meters during these 15 years[66] (Fig. 6.12). The detail surveying in the longitudinal profile (between ca 1295 and 1220 m a.s.l.) has shown a mean gradient of 13.9% and was distinguised by 28 segments with low gradient (3-10%), 10 segments with riffles (12-30%) and 29 steps with waterfalls. The local base levels were connected with large



x - x - continuation of PIII

Fig. 6.12: Cross sections of the Posam creek channel at the elevation: ca 1220 m a.s.l. (PI), 16 m higher upstream (PII) and 66 m higher (PIII) - surveyed in 1984 (after Froehlich and Starkel[66])

boulders, which since 1968 has been frequently reoriented (Photo 31, 50). In 1989 the surveying in the longitudinal profile was repeated (Fig. 6.13) and found, that the boulders upto 0.5-0.7 m in diameter were transported. Since then the creek has been continuously smoothing its profile, but the biggest boulders (3-10 m long) still form the steps in longitudinal profile. Among 17 marked steps, only 5 disappeared, in other 6 heights were lowered and the last 6 remained unchanged.

The opposite tendency of extreme and normal floods was observed at the outlet of a small tributary valley near Chong-Tong, where during the 1968 event the alluvial fan was dissected by the debris flow to about 10 m. After 15 years the existing gully was filled up by fine debris and a new inbedded fan only 2 m lower than the former one was developed.

The Jhepikhola creek (28 km^2 catchment), the right-side tributary of the Great Rangit river, with the relief energy of 2000 meters was surveyed in 1984[66]. There, traces of 1980 (3-5 September) flood were visible when after the rain above 500 mm, the water level in the channel

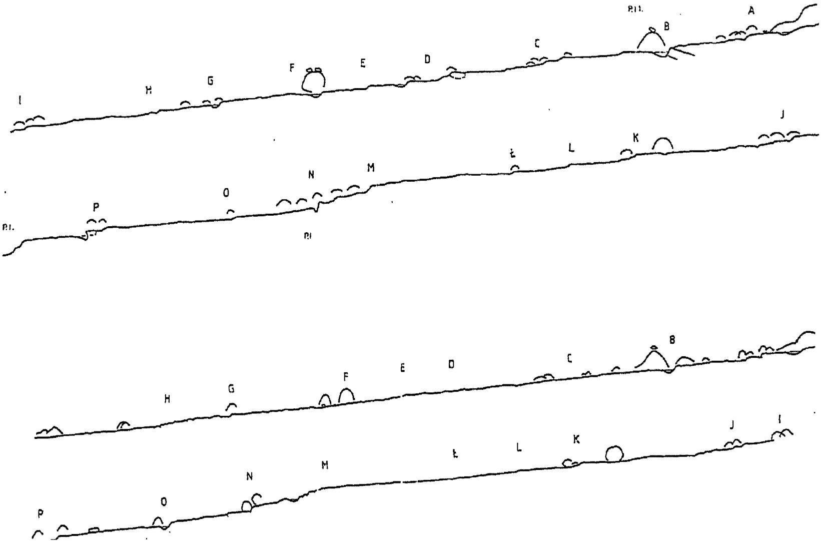


Fig. 6.13: Longitudinal profile of the Posam creek channel between 1220 and 1295 m a.s.l. surveyed in 1984 (above) and in 1989 (below). On the profile are shown pools, boulders and rapids deminishing in time (sites A-P indicated on both profiles) Transversal profiles PI-III (Fig. 6.12) are indicated

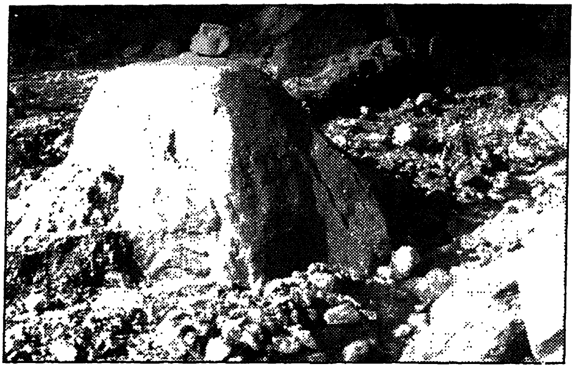


Photo 50: Rounded 7 m high rock (probably redeposited) with a boulder on the top indicating the extend of debris flow, in later stage excavated probably by hyperconcentrated flow (December 1968) (by L. Starkel)

(19 m wide) had risen to about 9 m, the creek carried blocks upto 7 m in diameter; the calculated discharge reaching 420 $m^3 s^{-1}$ and the specific run off probably about 15 $m^3 s^{-1} km^{-2}$. Revegetation has started and after four years a new 1.5 m deep and 4 m wide channel was formed with a distinct transitional step-like profile, similar to the Posam creek.

The Rangnu creek near Bannockburn TE, was covered in 1968 by coarse debris with a single block of 5-10 m in diameter at the whole of its 100 m width (Photo 30). After 15 years the main valley floor has been completely revegetated by trees upto 15 m high, shrubs and high grasses, giving even the shade for a couple of black panthers (Photo 51). Two cross sections have been surveyed, one 50 m and the other 20 m wide, in February 1984, November 1986, September 1987, July 1988 as well as repeating photo series afterwards[123]. Waterfalls and rapids are found to exist in this reach during the whole period (Fig. 6.14). In 1984 there were found the distinct traces of 1980 "medium" flood, when 3 m high gravel bars were formed. Next annual floods caused the rise of water level by 2 m and the boulders upto 40 cm in diameter (locally to 1 m) were found to be removed (Photo 32-34). The presence of coarse gravels every year at the outlet of the left-side tributary was connected with local heavy rains creating landslides and debris flows in this catchment (200 mm on 11 September 1986, 330 mm from 8 to 13 August 1987 and then 167 mm at 19 October 1987) (Photo 52). It was observed in July 1988, that the water covered the total width of the channel rising to 0.5 m after night rain of 73 mm.

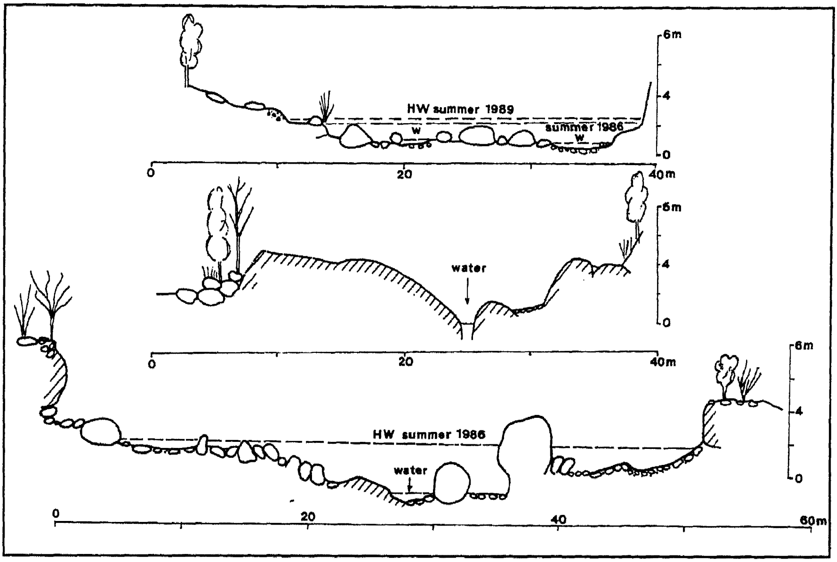


Fig. 6.14: Cross-sections of the Rangnu river at Bannockburn T.E. with surveyed flood water level from 1986 and 1989. Plain 4-6 meters high was transformed during 1968 flood and no more inundated

hoto 51: The revegetated Rangnu valley floor in 1987. The same section after October 1968 flood was presented on Photo 30 (by W. Froehlich)

The Kalijhora creek forms at its outlet to the Tista an alluvial fan 200 m long and 150 m wide. The whole form surveyed several times since 1986,[123] is located below the Tista high water level mark from October 1968 (Photo 53). The coarse debris carried that time by the Kalijhora were deposited as a fan at least 500 m from the present Tista and later dissected by the creek. Every year the Kalijhora creek remodels the alluvial fan carrying fine and coarse gravels (Fig. 6.15). These patterns depend also on the relations between the Tista main floods and the Khalijhora local floods (Photo 36, 37).

Photo 52: Fine debris deposited after heavy downpours on big boulders in the channel of the tributary creek between Bannockburn and Ging T. E. (1987) (by W. Froehlich)

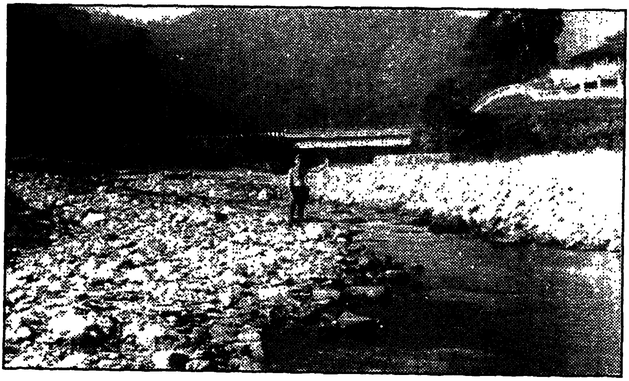
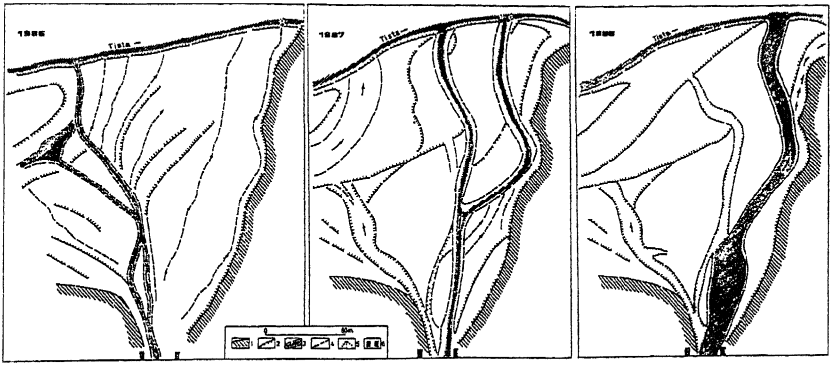


Photo 53: Outlet of Kalijhora creek to the Tista river. On the right the bungalow where the mark of the high water level from 1968 flood is located just below the main building (1986) (by W. Froehlich)



1. Steep slopes, 2. Edges, 3. Water (river), 4. Small paleochannels, 5. Small fans, 6. Bridge

Fig. 6.15: Kalijhora alluvial fan changing its surface surveyed in 1986, 1987 and 1988

The Little Rangit near Pul-Bazar (catchment of 75 km^2) was surveyed only in 1984 when an active channel of 10-15 m wide and 2-3 m deep was observed instead of wide floor covered by boulders (Fig. 6.16). It means that the river of this size turned partly to the previous shape and on the higher bars overlaid by overbank sands, new fields were formed and started to be cultivated again. The measurements of the lowest water level at Singla Bazar (downstream of Pul-Bazar) made between 1974 and 1983 have also shown a slight tendency to downcutting of the order of 0.5-1 m disrupted by aggradation caused probably by shifting channel bars (Fig.6.18).

The observations on the Balasan river valley are related only to the reach near the outlet of the Ambootia landslide valley[65]. A great colluvial fan in October, 1968 pushed the main river towards the right bank and the boulders (1-4 m in diameter) are exposed in the channel sides (Photo 23). The fan surface was built up by finer debris during the reactivation of landslide in 1983 (Fig. 5.22) and later dissected

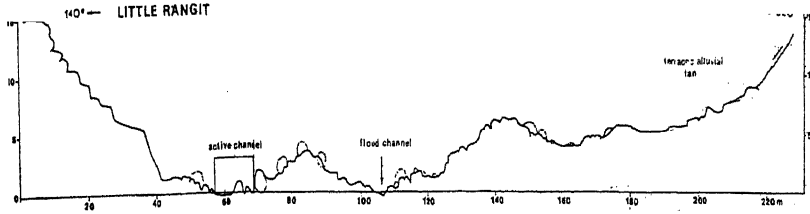


Fig. 6.16: Cross-section of the Little Rangit river channel near Bijanbari surveyed in 1984 (after Froehlich and Starkel[66])

several meters deep at its margin. This infill of coarse material in the Balasan channel caused aggradation downstream in the form of wide side bars upto the outlet of Balasan from the mountains.

In the Tista Valley the first detailed observation were made at the junction with the Great Rangit valley. First of all the changeable position of bars 2-3 m high and of the main channel of the Great Rangit was observed (Photo 49, 54-56). The channel banks after the 1968 event were revegetated at elevation between 20 and 5-7 m above the low water level e.g. down to the mean elevation of annual high water level. At this reach as well as 2 km downstream (upstream of Peshok Jhora) the repeated nivelations (Fig. 6.17) show a very distinct upbuilding of boulders and gravels by sandy layers during the high water level and the formation of a narrow flood plain 5-7 m high slowly reoccupied by vegetation from the valley side.

Photo 54: The junction of the Tista river with the Great Rangit with shifted bars in February 1984 (by W. Froehlich)

The gradual lowering of the low water level after 1968 flood at Tista Bazar near Anderson Bridge shows a deepening of 1.5-2.0 m between 1968 and 1983 and in the decade 1974-1983 about

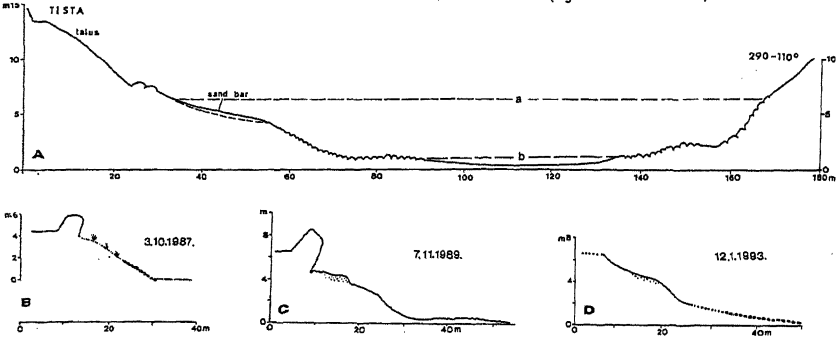
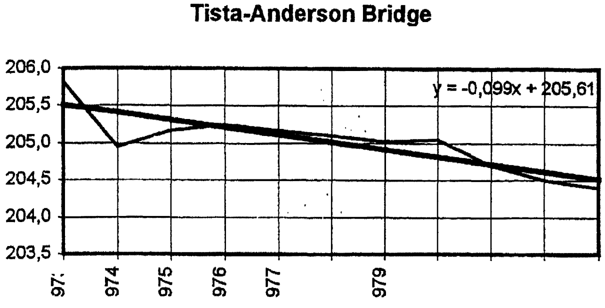


Fig. 6.17: Cross-section of the Tista river channel upstream of Tista Bazar surveyed in 1984 and resurveyed in 1987, 1989 and 1993

10 cm yr^{-1} (Fig. 6.18). This is connected with the washing of finer material and the formation of the pavement built of coarse boulders at the channel floor[66]. The size of boulders depend also on the supply by debris flows and rockfalls from the tributary valleys (Photo 35). Due to that deepening also the annual floods do not reach the level of the higher boulder bars and revegetation of them follows.


Tista-Anderson Bridge

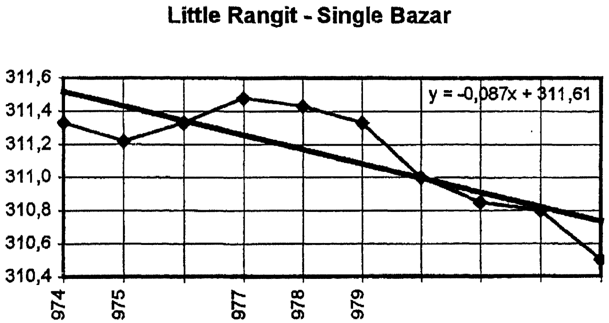

Little Rangit - Single Bazar

Fig. 6.18: Incision trend of Tista and Little Rangit river based on gradual lovering of minimum water level after 1968 flood

The measurement of grain size of deposits forming the 5-7 m high terrace in 1993 near Kalijhora creek outlet by T Kalicki and L Starkel[72] have shown the dominance of coarse gravels and boulders between 0.2 and 1.0 m overlaid by sandy flood deposits on their top. The narrow points bars built of sands and gravels upto 2-20 cm in diameter are found at the low water level along the convex channel banks. In other reaches such bars of 1-3 m high are being replaced every year.

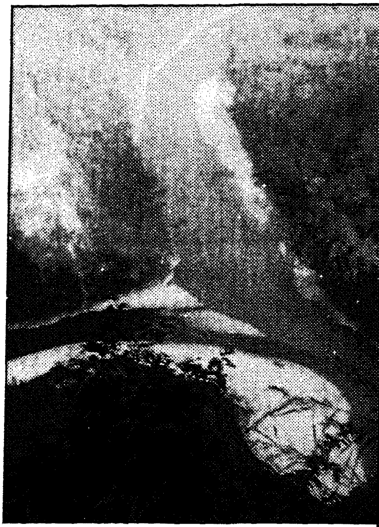


Photo 55: The same junction in November 1986 (by W. Froehlich)

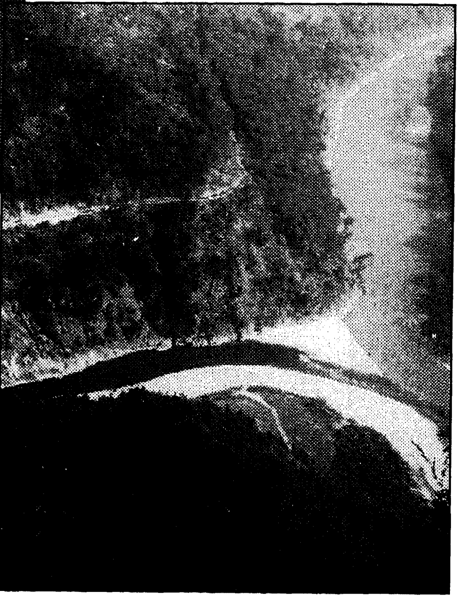


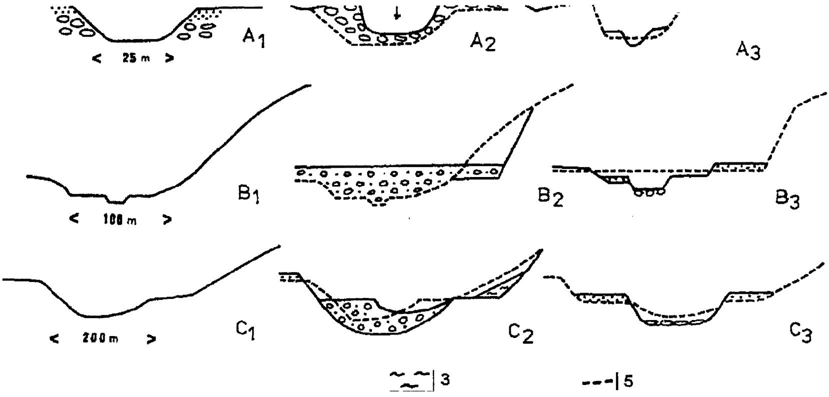
Photo 56: The same junction in November 1989 (by W. Froehlich)

Repeated, but not systematic observation on the river channels of various order and flood plains carried on from 1984 indicate the trends of evolution after the October 1968 flood. The general tendency of narrowing and incision of steeper gradient river channels are accompanied by the formation of step-like longitudinal profile (cf. observations of Brunsden *et al.*,)[142], which in fact reflects the tendency to smoothening of the river gradient in the presence of large boulders. In larger river this is replaced by washing of finer gravels and formation of bottom pavement. In overdeepened sections the deposition of fine material has taken place. The former boulder bars or debris flow tongues undergo a transformation into terraces by overbank deposition or in the 2-3 order streams these boulders are fossilised by slope deposits (Photo 5).

The study of a consecutive transformation of the valley floors during extreme events and normal monsoon floods makes possible the creation of model of the longterm tendency of evolution[66,143] (Fig. 6.19). Under natural condition the sequence of alternating cuts and fills show a distinct tendency to downcutting in the river valleys of various orders. After deforestation, the delivery of colluvial masses from slopes including big boulders helps in the damming the river channels and ultimate aggradation especially along the middle reaches of the mountain valleys (Fig. 6.20). Therefore, the gradient of these rivers has increased in last century. Only the Tista river with higher discharges during the rainy season is in a position to remove its channel deposits downstream upto the mountain foreland and thereby incising its channel in the bedrock in conformity with the rising mountain front.

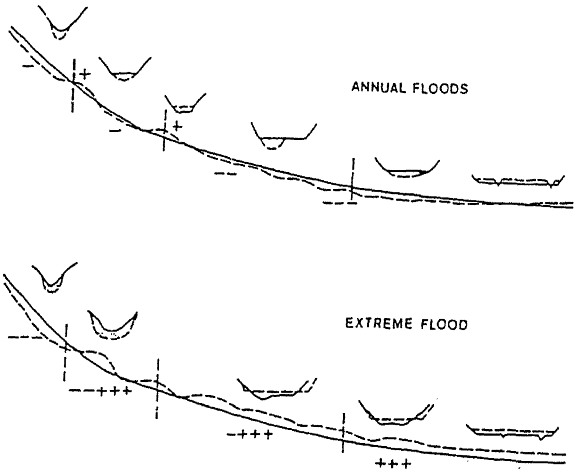
6.6 Channel Changes in Aggrading Rivers at the Mountain Margin

Steep slopes of the Darjeeling Himalaya fall abruptly on to the alluvial plains of the foredeep to the south. Decrease in the river gradients and widening of valley floors at the outlet from the mountains causes a rapid recession of river competence and transport capacity. As a result of that an extensive deposition over the alluvial fans and systems of braided channels (Fig. 6.21, Starkel[23]) causing annual changes of channel geometry[43,63,68,144] (Fig. 6.22 and 6.23).



Signs: 1. Coarse boulders and gravels (channel facies or debris flow), 2. Fine gravels and sands (overbank facies), 3. Colluvia, 4. New formed profile, 5. Previous profile

Fig. 6.19: Transformation of river channels of various size before the extreme event (1) After event (2) And during relaxation phase (3). Channels of various size: A - like Posam creek, B - like Little Rangit at Pul-Bazar, C - like Great Rangit or Tista river (compiled by L. Starkel)



+ means aggradation, – means downcutting

Fig. 6.20: Different tendencies of vertical position of channels in longitudinal and transversal profiles during annual normal floods and extreme floods (after Starkel[1], Froehlich and Starkel[66])

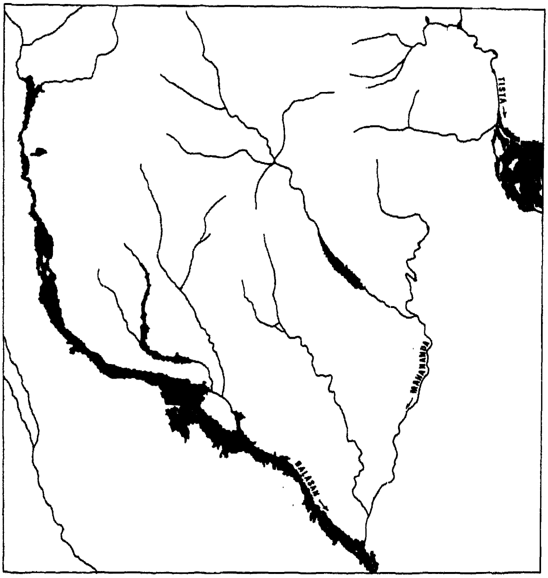
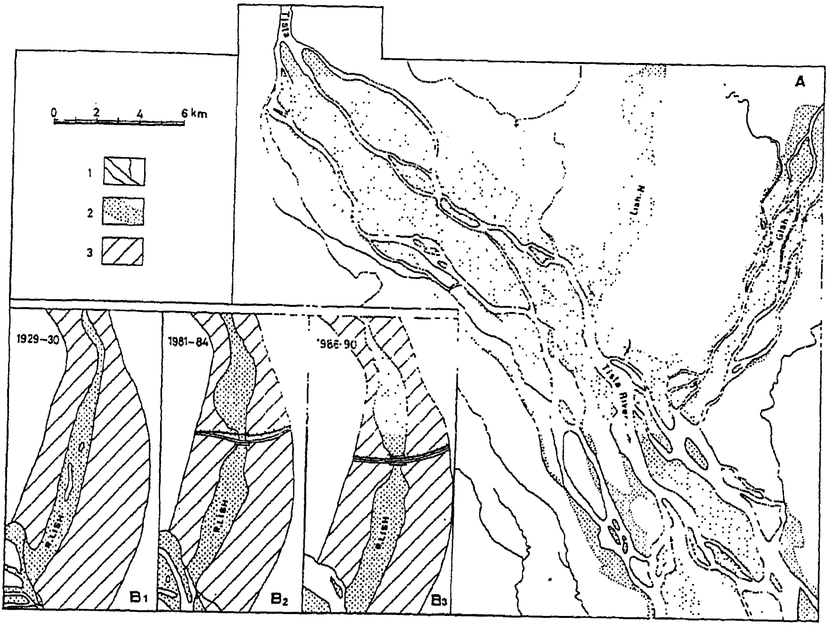


Fig. 6.21: Unvegetated bars in the river channels at the mountain margin (after satellite picture – compiled by P.Prokop)



1. River channel, 2. Sandy-gravely bars exposed during dry season, 3. Floodplain of the Lish river

Fig. 6.22: Braided Tista river and its tributaries at the mountain foreland A–After survey before 1968, B–Lover course of Lish river drying out surveyed in the periods: 1929-30, 1981-84 and 1986-90.

The outlet of the Tista river from the mountain differs from the others, smaller ones in character. In the marginal mountain part the narrow valley floor of the deeply incised Tista valley plays simultaneously the role of a river corridor. The narrow channel create condition for overdeepening . Even at low water levels the water velocity reaches 2 m s^{-1} . Especially the straight reach of Tista overdeepened in the bedrock creates the hydrodynamic conditions favourable for the bed load transport and removal of coarse debris. Therefore in that reach the depositional forms are missing. The point bars appear just at the outlet to the plain and extends over the wide expanse of the fan surface with braided channel pattern (Photo 38).

With increasing distance from the mountain front the selection and grading of grain fractions follows. At the distance of 15 km the sandy deposits prevail in the river corridor. These fine sediments in the dry season are being redeposited as the bed load. The presence

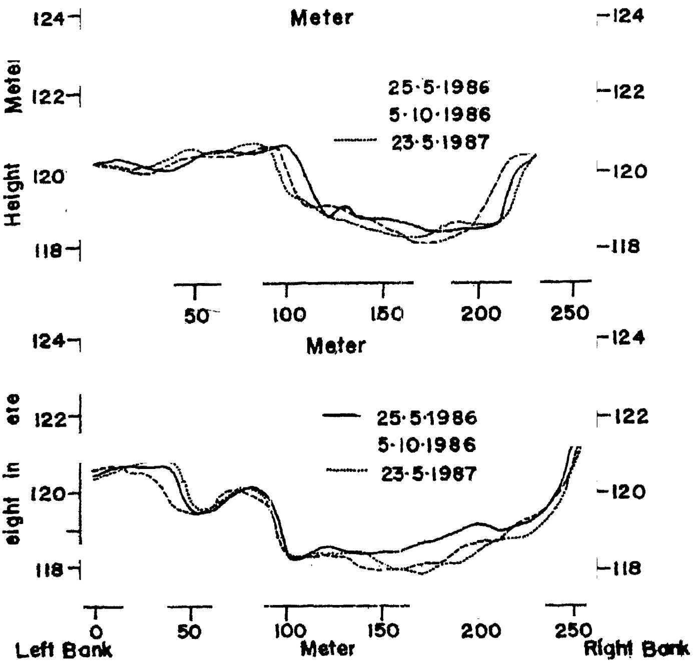


Fig. 6.23: Changes of the channel cross-sections of the Mahananda river before and after rainy season near Siliguri (after Sarkar[68])

of insignificant amount of clay can not help in their consolidation and cause reworking, leading to lateral migration of channel branches and their avulsion even during medium water level.

On the contrary beyond Tista in the other rivers of the foreland the contemporaneous deposition of coarse channel sediments (gravel and boulders) is gradually progressing upstream into the mountains. This is true in case of the Balasan, the Mahananda as well as the Lish and the Gish river valleys. Especially in the Balasan river valley, the aggradation is progressing about 15 km upstream up to the outlet of landslide valley of Ambootia (see Chapter 5.7). The annual floods remove these boulders to the foreland, where follows their intensive exploitation during dry season (Photo 40). A good example is the Balasan river down to the road bridge near Siliguri, where every year the total deposited mass of coarse sediments is being removed and the elevation of bed level in the period 1984-1998 has not shown any distinct change. Therefore the building up of flood embankments is not necessary. These observations were made in the period of stable regime and not during catastrophic flood and therefore this equilibrium should be taken as temporal.

Much more intensive rate of deposition at the mountain front is observed in the valleys of the eastern tributaries of the Tista river especially at the outlet of the Lish and Gish rivers[61,63] where during the years 1984-1996 we observed continuous aggradation of the front cleared of jungle (Fig. 6.22). The rate of deposition of gravels and boulders may be calculated by measuring the heights of living trees and bushes. The highest deposition rates here may reach 3 meters during 10 years. These braided channel floors several kilometres wide, dry in winter are being flooded every year (Chapter 5.6).

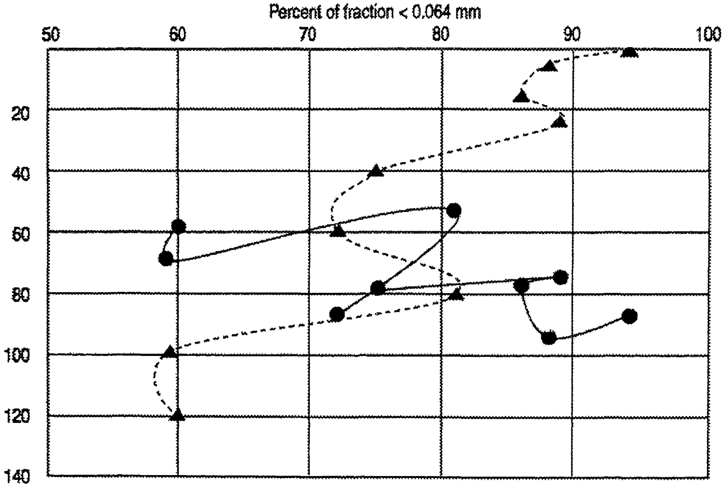
These dynamic reaches are controlled by rapid flooding and deposition connected with dispersion of energy, with widening of river channels as well as with rapid infiltration of water in permeable sediments. The sedimentation of coarse sediments, is progressing upstream into the mountains. This is connected with the overburdening of river caused by the direct delivery of coarse debris supplied by numerous landslides and the degraded coal quarries[43,62,113,114].

The alluvia at the bottom of the described fans are built of rounded coarse gravels and boulders upto 1 m in diameter. This zone extends 1.5-3 km from the mountain front and has steeper gradient. At the margins the gravels may be covered by the coarse sands, several centimeters thick. Probably part of these unvegetated sediments is the product of erosional rejuvenation of older bars. At several locations observed during last 15 years, including bridge crossings of the Lish and the Gish rivers, no distinct changes in the elevation of flood corridors were observed. This lack of aggradation is probably connected with a very intensive exploitation of gravels and boulders, which is replaced by the supply of fresh material from headwaters.

Due to the lack of other quarries the coarse alluvial deposits are the unique materials used for various construction purposes. Among them are the embankments and other anti-erosional constructions stopping the lateral channel migration. Especially distinct is a long embankment several meters high running along the Tista banks upto the Bangladesh frontier, build of big boulders derived from the root zone of fans. These constructions play an important role in regulating the water courses and deposition of fine fraction. They play a very positive role in limiting lateral migration and avulsions to the several kilometres wide flood plain zone between embankments. Such braided belts are modelled by lateral erosion, migrating bars and rare avulsions. Going downstream an essential role in the Tista channel zone is played by the bedload of sandy fraction, causing the transformation of braided pattern during each rise of water level, several times every year.

In the several kilometres wide belt of flood zone of the Tista near Jalpaiguri two distinct levels of the floodplain may be distinguished. The lower one 1.2 m high is built of silts and clays with intercalations of sands. This unit 80-100 cm thick is underlain by the gravels of the channel facies. The upper 10-30 cm thick cover of overbank deposits is connected with low concentration of suspended load rising during annual floods only to 1500 g l^{-1}.[145] Similarly in the mountain reaches these overbank deposits as characterised by a very low concentration of ^{137}Cs, indicating the delivery of material from slopes affected by intensive mass movements. Part of the fine particles is also coming from abrasion of boulders and gravels, which does not contain this radioisotope. This also causes the decline of ^{137}Cs concentration.

This lower flood plain is inundated every year. Near Jalpaiguri it is restricted mainly to fragments between wing dams. Similar elevation is reached by most of point bars and central bars build only of sandy fractions. Despite the annual flooding these bars do not have



(dotted line over bank deposits in middle part of central bar; solid line-channel deposits on 60 cm below top of central bar)

Fig. 6.24: Deposition of overbank sediments of Tista river near Jalpaiguri

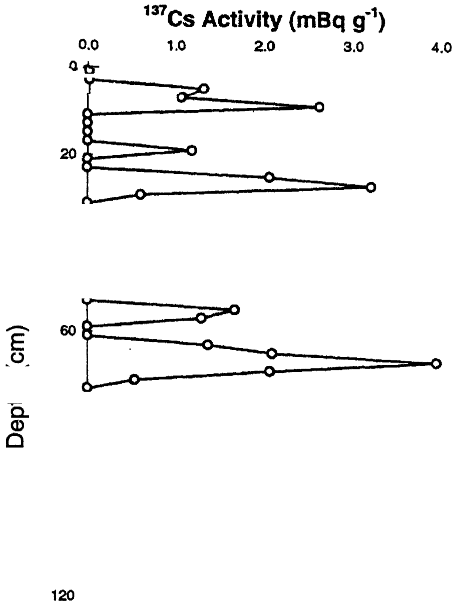


Fig. 6.25: Vertical distribution of ^{137}Cs in the overbank deposits on the Tista flood-plain near Jalpaiguri

the blanket of overbank deposits, because of the lack of vegetation cover which does not permit the deposition of fine fraction (Fig. 6.24). These bars belong to the most dynamic forms in the wide flood channels.

The preliminary measurements of radioisotopes ^{210}Pb and ^{137}Cs indicate, that the vertical accretion of the Tista flood plain near Jalpaiguri, facilitated by the wing dams may reach 2-4 cm yr^{-1} (Fig. 6.25 and Froehlich and Walling[146]). This high deposition rate reflects the efficiency of the erosional systems of the rising Himalaya. The relatively low concentration of suspended load is compensated by high bedload of sandy fraction[138]. Due to a quick lateral channel migrations and avulsions the overbank deposition is dispersed across a very wide zone and therefore the vertical accretion is reduced.

The higher floodplain, rising to 2.5 m in the Tista valley near Jalpaiguri is restricted to several dozens of meters wide benches located at the base of 8-12 m high terrace scarp. After local observers this terrace near Boogadong (S of Jalpaiguri) has been flooded last time in 1968. Similar elevations are reached by the fragments of central bars, several kilometers long, also formed during October 1968 flood.

One of larger forms covered by grass is in its highest part settled and transformed in agricultural land. It is built of coarse sands overlain by silty-clayey overbank deposits 80-100 cm thick. Starting from 1968 its lower marginal parts are extending by lateral accretion of overbank sediments. The analysis of cartographic sources shows that such large island may be created only during catastrophic floods. These data and informations on the previous avulsions[23, 131] indicate that the rare extreme floods play a leading role in the sculpturing of alluvial fan surfaces in the mountain foreland.

7

ROLE OF EXTREME EVENTS IN THE TRANSFORMATION OF THE DARJEELING HIMALAYA

Types and Frequency of Extreme Events

The presented studies helped to identify four types of extreme events leading to the transformation of landscape in the Darjeeling Himalaya: regional continuous rains, local downpours, allochtonous floods (in the Tista valley) and earthquakes (Fig. 5.12).

The regional heavy rains with precipitation totals 500-1500 m in 2-4 days cause the simultaneous passing of various thresholds in the slope and channel systems and play an leading role in relief evolution. Their random distribution (1899, 1950, 1968) create the conditions for various relaxation after each of these events.

The local transformation on slopes and in smaller catchments is connected either with local heavy downpours or superposition of downpours on low intensity continuous rains passing together 300-500 mm (September 1980 in Jhepikhola, 17 July 1987 near Kurseong). Such events are registered every second year at various places and at one locality their recurrence interval fluctuate between 2 to 10 years.

The allochtonous flood waves originate upstream of the Darjeeling Himalaya, also due to rapid melting of snow and ice in the Kanchenjunga massif. In the case of October 1968 flood the 20 m high waves of the Tista was connected with the second concentration of rainfall in the SE part of Sikkim.

Though the occurence of earthquakes is random, but their appearance during the rainy season may cause substantial changes in slope morphology creating various mass movements (Fig. 5.12).

Changes During Regional Continuous Rains

The unusual changes during the continuous rain like in October 1968 are controlled by steep slope gradients and lithology. The high infiltration rate on sandy-silty soils causes the threshold of the overland flow to be passed only on the slope fragments and never on their whole length. On the contrary mainly 1-3 m thick regolith on the steep slopes after several hundred millimeters of rain passes the threshold of liquifaction being supported by piping processes. The deeper infiltration along the joints causes the formation of deep landslides. The final results of such continuous rain are the removal of the weathered mantle on extensive slope surfaces, increase of drainage density with exposure of more resistant beds and the appearance of the step-like slope profiles- the first signs of structure controlled relief in this youthful landscape.

The simultaneous rapid water level rise in the rivers combined with very irregular delivery of coarse debris from the slopes (also from undermined channel sides) and tributary creeks causes a very differential aggradation. The coarse debris and fine debris segments alternate and later depending also on the pre-event bedrock topography and channel gradient, undergoes erosion or deposition. In the tributary valleys with gradients, above 5-15% the hyperconcentrated flows and debris flows are frequent. The main characteristic feature of extreme continuous rains is a simultaneous passing of thresholds transforming both the slope and channel systems[3, 147] (Fig. 7.1).

The erosion and sedimentation are accompanied by destruction of vegetation cover and damages of buildings and roads. Over the slopes the trees and tea bushes were either totally removed or in some cases only replaced. The channel banks and steep valley sides were totally

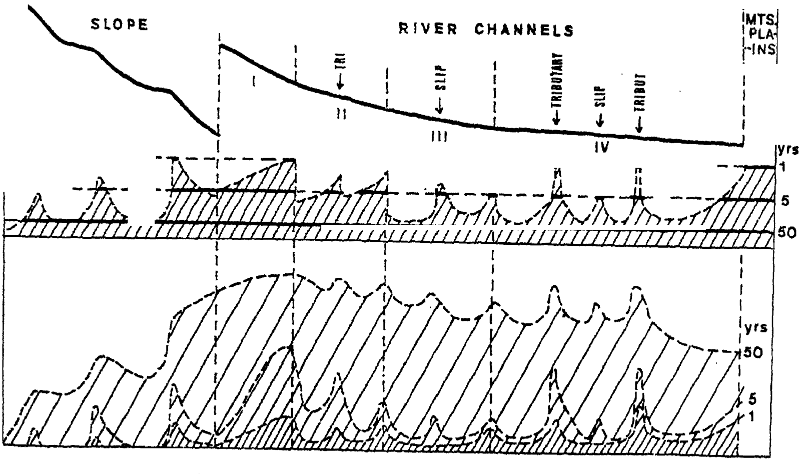


Fig. 7.1: Frequency of threshold events and relative scale of changes in the longitudinal profile of slopes and river channels (after Froehlich et al.[91, 123])

bared of vegetation. The roads on slopes in 1968 were in thousands of places covered by debris from above or broken by slumps and undermined by gullies. The damages in the valley floor were connected with aggradation upstream of bridge barrages, breaking of them or passing by river avulsion.

Role of the Normal Rainy Seasons

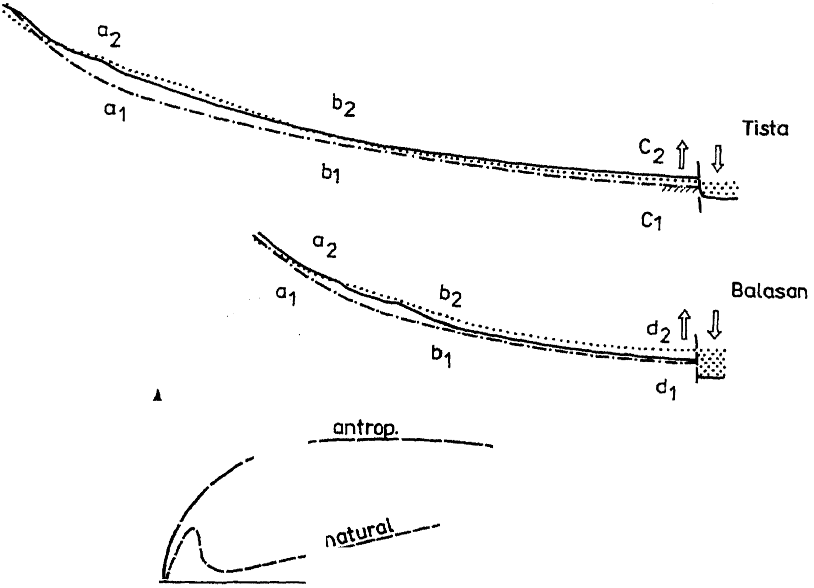
The normal rainy seasons during the interval time between two extreme event leads to the reaching of the previous equilibrium. In this processes a very important role is played by the revegetation of damaged slopes and floodplains. It was observed after the 1968 event the revegetation followed in 5-15 years time[66]. Only in the case of the great Ambootia landslide valley the stabilization follows at much slower rate[65] due to hydrogeological reason. The relaxation period is connected with changes in sediment load, formation of a new soil cover and filling up of various gullies and depressions by fine material. But the total relaxation is impossible because the slope gullies initiate a new tendency of slope transformation and great boulders delivered to the river channels delay or even totally block the incision in the rising mountains.

Long-Term Tendency of Relief Evolution

For the better understanding of long-term evolution the better recognition of the frequency of extreme events and length of the relaxation time is of great importance (Fig. 7.1). The comparison of the geomorphic effects of two following events in 1950 and 1968[1] indicates that the effects of the second event were limited in the areas where debris flows of 1950 year occupied all more favourable areas. At the sites where the niches and gullies were revegetated with some delay after 1968, it was observed that the repeated slumps and flows occurred during heavy downpours till the 1980th (at Bannockburn TE) (Photo 8). Along the river beds and on the flood plains after 20-30 years the recovered plant cover is so dense and resistant, that its next destruction after long relaxation time is not possible.

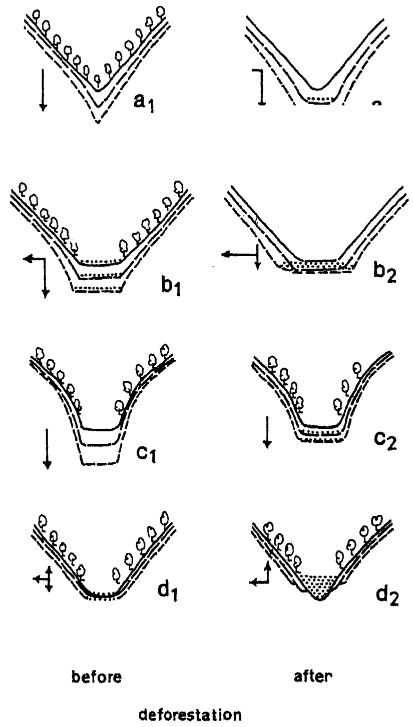
From the enclosed model it may be concluded that the increase in the frequency of extreme events is leading to lowering of their geomorphic effectiveness and of relaxation time. But from the other side every next event creats a higher drainage density over the slope and thus follows the acceleration of sediment delivery to the channel.

A distinct difference in the long-term tendency may be observed between the period with natural vegetation and after the human intervention (Fig. 7.2 and 7.3). If we consider the present-day uplift of the order 3-4 mm yr^{-1},[78] V-shaped valleys in the forested areas,[1,148] then only the great Tista river follows the uplift with downcutting. After deforestation the annual suspended load (see Chapter 5.2 and 6.2) measured by the denudation rate of the order of 1 mm during normal year, is multiplied on the slopes during extreme event to at



Continuous line indicate existing long profile: a. Upper reach (a1 - natural trend, a2 - tendency after deforestation), b. Middle reach (b1. and b2 - as a1 - a2), c - Outlet of Tista from the mountains with differenciated tectonic tendencies (as a1 and a2), d. Outlet of smaller rivers (Balasan, Lish), d2 - show distinct aggradation after deforestation. The arrows show the main tendency to uplift or subsidence. Below changes of the sediment load in the longitudinal profile of smaller rivers under natural conditions and after deforestation

Fig. 7.2: Tendencies of transformation of longitudinal profiles of greater river (eg. Tista) and smaller one (eg. Balasan) dissecting Darjeeling Himalaya (after Froehlich and Starkel[148])



a - Upper reach, b - Middle reach, c - Outlet of Tista from the mountains, d - Outlets of smaller rivers.

Arrows show main trends; discontinuous line - tendency to erosion; dots - to aggradation

Fig. 7.3: Tendencies of transformation of valley cross-sections before and after deforestation (after Froehlich and Starkel[148])

least 20 cm[1]. Therefore in the river valleys with irregular summer outflow (excluding Tista) this surplus of coarse sediment load is deposited causing an opposite tendency to the aggradation, which from the foreland enters along the rivers into the mountains[148].

8

PRESENT-DAY AND FUTURE OF THE DARJEELING HIMALAYA

The present-day environment and economy of Darjeeling Himalaya are closely connected with each other and lead inevitably to the acceleration of various circulations of matter. Thinking of the future of this mountain area we should take into consideration the interdependent longterm environmental changes as well as the economic and social progress but parallely try to evaluate the threshold values which should not be passed to preserve the substantial equilibrium in the natural resources.

The natural trends of evolution of young mountains are the fundamental factors, which may not be stopped[149]. These include the tectonic uplift and parallel subsidence of the Himalayan foredeep of slopes. In the deforested catchments with high slope degradation incision is often blocked by the deposition of coarse debris in the valley floors and the aggradational rise of the channel gradients. In the conditions of monsoonal circulation and dense vegetation covers the weathering rate of rocks is very high. The parallel high rate of slope degradation depend on the frequency of extremely heavy rains. In the conditions of the global warming this frequency may increase[150,151].

Analysing the land use changes in the last 150 years we observe a continuous restriction of the forest areas,[152] (Table II), increase of the cultivated land (with exception of the tea plantations), and rapid rise of areas taken by settlements and roads (Fig. 3.15 and 5.13). The rapid decline of forests is especially visible on the tea garden properties, where most of the jungle patches with multistory vegetation in 1968 were changed to the shrubs and open woodlands during the next 15-25 years. Many new roads have undermined and drained slopes. In the developing towns and along roads many multi-storied buildings were constructed, increasing the basic load of slopes. All these active trends create an increasing potential menace in case of next catastrophic rains (Table VI).

Table VI: Estimated population vulnerable to landslides

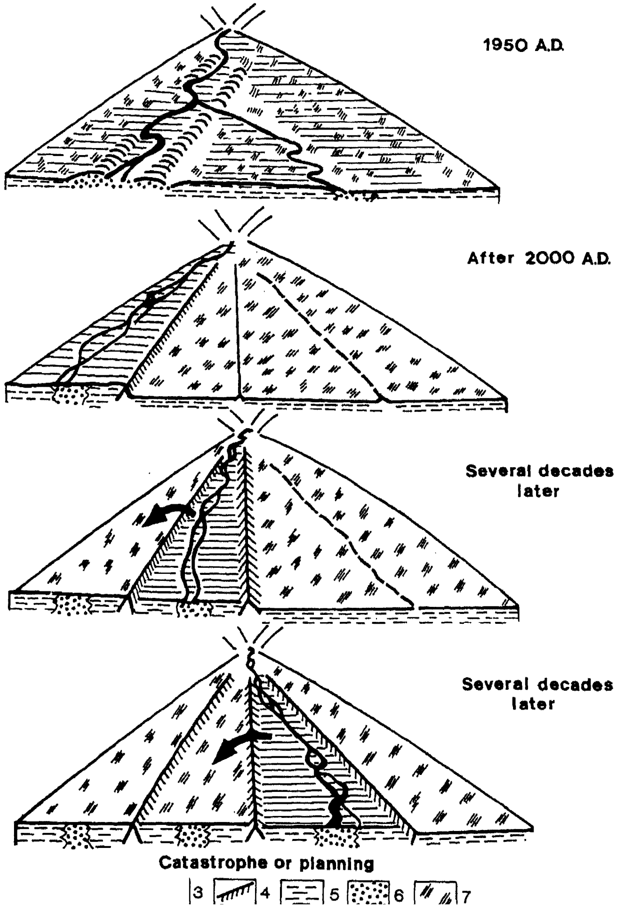
Name of blocks	No. of inhabited villages	Total population	Persons vulnerable to landslides	Population in percent vulnerable to landslides
Darjeeling-Pulbazar	23 (16)	80,276	55,844	69.57
Jorebungalow-Sukhiapokhri	39 (10)	70,233	18,008	25.64
Rangli-Rangliot	20 (15)	51,825	38,868	75.00
Kalimpong I	72 (12)	70,949	11,824	16.67
Kalimpong II	64 (23)	78,806	28,320	35.94
Gorubathan	27 (13)	32,362	15,581	48.15
Kurseong	38 (20)	55,289	29,099	52.63
Mirik	19 (7)	28,519	19,963	70.00

Figures in parenthesis indicate the number of villages susceptible to landslides
Source: Compiled after Plan for Darjeeling Hill Areas 1980-1985[157]; Mid Term review and Annual Plans 1983-1984 and 1984-1985.

In these circumstances many authors discuss the methods and mechanisms of the rational management of natural resources and the counter actions against catastrophic events but in view of the population explosion in India such measures are very difficult to implement. The explosion is followed by the rise of demand of land under settlement, cultivation and road pattern, rise of demand on energy and water supply. This situation originates the question of employment. Therefore in Darjeeling Himalaya time has come to consider new directions of economy and employment: tourism combined with the rising standard of accommodation, handicrafts, modernisation of tea plantation and extensive programme of reforestation.

The fundamental question is the energy demand. Till now the most important among the main sources of energy are the low-energetic coal beds. Their exploitation is leading to the formation of extending landslides (especially localised at the undercuttings of roads). Due to relatively high costs of imported oil the construction of a network of small hydro-power stations should be considered. There still exists in Darjeeling a high demand of firewood (cf. Chapter 5.4).

From year to year the water demand has increased drastically, both in the towns, in villages and on tea plantation. The forest clearance and dissection of the upper portions of slopes has been reflected in the lowering of ground water level and drying of springs during the winter season. This phenomenon was observed several times i.e. at



1. Existing river, 2. Levees, 3. Flooded zone, 4. Embankments, 5. Overbank deposits, 6. Channel deposits, 7. Settled and cultivated areas, 8. Shift of flooded belt

Fig. 8.1: Suggested changes in land use (shifting of flooded and cultivated areas) over alluvial fans in the Himalayan foredeep (after Starkel[153]*, changed)*

the Bannockburn TE. Therefore the upper slopes should be reforested as soon as possible serving as protective zones for water management.

In the urbanised areas, construction of many multi-story buildings with deep seated foundations are being carried out at present. But in such conditions, when the loading of slopes built of jointed bedrock is high, the passing of slope equilibrium is very probable as well as dangerous, especially during the earthquakes combined with extreme rains. Similar disturbances of slope equilibrium were observed along roads, where walls and terraces were constructed.

The future of Darjeeling Himalaya does not look to be optimistic. The basic condition is the reforestation of the mountain slopes and reconstruction of more natural and delayed circulation of water. The second important problem is that of water pollution. To prevent the erosional and gravitational processes immediate restriction to quarrying of coal along roads and of heavy constructions over slopes is very important.

For the future planning we should consider not only the erosion in the rising mountains as the natural trend, but also the deposition in the subsiding foredeep. The concentration of water in large water reservoirs which undergo rapid siltation may only for several decades reduce the damages in the plains. Therefore in the coming decades we should consider the alternate construction of great polders with free sedimentation and the parallel planning of shifting of settlements and arable land[128,153] (Fig. 8.1).

9

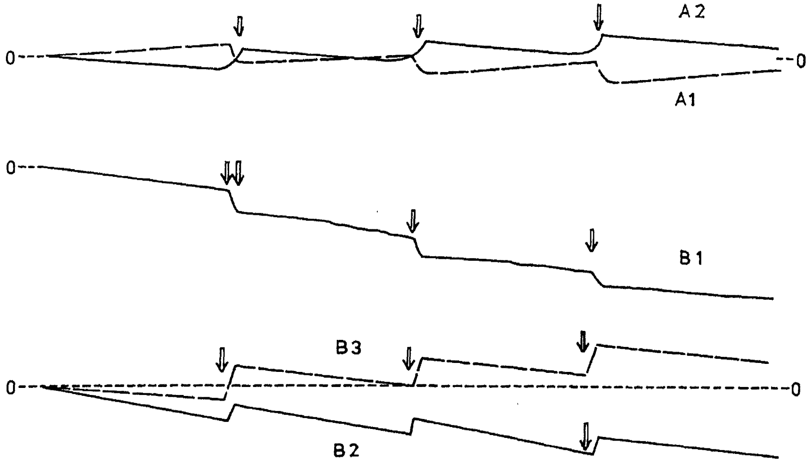
CASE OF THE DARJEELING HIMALAYA IN THE CONTEXT OF ENVIRONMENTAL CHANGES IN THE MOUNTAINS OF MONSOONAL TROPICS

The presented example of marginal part of the Sikkim Himalaya represents several features common to the monsoonal tropical mountains as well as some specific signs which distinguish this part of Himalaya from other tropical mountains of southern Asia.

Among the common ones there are precipitation and temperature regime controlling the course of runoff and denudation as well as rate of soil development and vegetation. Among the spatially differentiated specific features are the type and course of tectonic evolution, lithology as well as time and directions of human intervention[36].

The most common feature of the monsoonal mountains is the climatic regime, although the annual precipitation may fluctuate from less than 2000 mm in Western Himalaya to 12,000 mm on slopes of the Meghalaya plateau. A common mark is the randomly distributed heavy downpours and continuous rains. The time of start and duration of the rainy season shifts in time from the east towards west. The Darjeeling marginal Himalaya are just close to the mean values and are characterised by a dominance of chemical weathering and evergreen forests. The surplus of water during the rainy season decides on the run off exceeding 40%.

The course of relief evolution and rate of geomorphic processes is differentiated depending on tectonic, orographic and lithologic condition. First of all we may distinguish two types of mountains of various tectogenesis. The old planated blocks of the Deccan Plateau or Meghalaya after uplifting have still preserved thick lateritic regoliths, which in the marginal zones are exposed to denudation. On the contrary the rising up Himalayan young orogenic structure undergoes much more intensive degradation supplemented by parallel rock weathering. The course of dissection depends on the differentiation of uplifting and subsidence. The active faultlines at the margin of Sikkimese sector of Himalaya are different from the flat overthrusts of Western Himalaya and have more in common with the margin of the Ghats or Meghalaya. Therefore the marginal part of the mountains in our sector is deeply dissected and the erosion proceeds upstream (Fig. 9.1).



A1 -General tendency to downcutting, A2 - General tendency to aggrada-tion,
B1 -Natural tendency to downcutting in uplifting mountains of monsoonal climate.
B2 -Delayed tendency to downcutting after deforestation in upper mountain courses.
B3 -Tendency to downcutting changed to aggradation after deforestation in lower courses

Fig. 9.1: Main trends of channel vertical changes during repeated extreme events (arrows)

The next differentiation is connected with lithology, which controls a whole palette of landscapes from tropical kegelkarst and granitic tors to badlands. The medium resistant gneisses, schists and sandstones and their permeable soils under the circumstances of high uplift rate created a young rough landscape undergoing transformation by debris flows and other mass movements.

Finally the mountains of the monsoon tropics differ in time and character of deforestation, which in several regions goes several centuries and millenia back and in some areas just started or is expanding (like in Nepalese Himalaya). In case of the Darjeeling Himalaya the highest rate of deforestation appeared in the mid- 19th century and in some parts is expanding again in the last decades due to the population pressure. A specific type of land use by the tea gardens creates in the whole monsoonal mountains specific conditions for soil erosion and soil protection. The deforestation is there to the greatest extent being responsible for the simultaneous response of slope and channel processes to catastrophic rainfalls and change of incision tendency in the river channels of the mountain front towards aggradation proceeding upstream.

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REFERENCES

1. Starkel L. 1972. The role of catastrophic rainfall in the shaping of the relief of the lower Himalaya (Darjeeling Hills). *Geographia Polonica* **21**, 103-160.
2. Starkel L. 1972. The modelling of monsoon areas of India as related to catastrophic rainfall. *Geogr. Polonica* **23**, 151-173.
3. Starkel L. 1976. The role of extreme (catastrophic) meteorological events in the contemporary evolution of slopes. [in:] *Geomorphology and Climate*, (ed.) E. Derbyshire, J. Wiley, 203–246.
4. Dey B. 1977. The summer monsoon in South Asia. *Geographical Review of India*, **39**, 3, 266-281.
5. Das P.K. 1987. Short- and long- range monsoon prediction in India. [in:] *Monsoons*, (eds.) J.Fein and P.C. Stephens, J. Wiley, **17**, 549-578.
6. Dhar O.N. and Nandargi S. 1998. Floods in Indian rivers and their meteorological aspects. [in:] *Flood Studies in India*, (ed.) V.S. Kale, Geological Society of India, Bangalore, *Memoir* **41**, 1-25.
7. Ananthakrishnan R. and Krishnan A. 1962. Upper air changes over India and neighbourhood associated with the south-west monsoon. *Curr. Sci.* **31**, 133-136.
8. Tripathi R.S., Uma Shankar and Pandey H.N. 1995. Present Status and Strategies for Ecorestoration of Degraded Ecosystem at Cherrapunjee. [in:] *Ecorestoration of Degraded Hills*, (eds.) B.K. Tiwari, Surendra Singh, Kaushal Publications, Shillong.
9. Singh S. 1996. Technical Report on Delineation of Geo-Ecological Zones in Meghalaya. Report No. GE/11GC/SR(I)SS.
10. Ramdas L.A. 1968. Monsoon and rainfall pattern in the Indian subcontinent. [in:] *Mountains and Rivers of India*, IGU Congress, Calcutta, 230-257.
11. Mooley D.A. and Parthasarathy B. 1983. Droughts and Floods Over India in Summer Monsoon Seasons 1871-1980. [in:] *Variations in the Global Water Budget*, (eds.) A. Street-Perrott *et al.*, Dordrecht, D. Reidel, 239-252.
12. Gupta A. 1988. Large floods as geomorphic events in the humid tropic. [in:] *Flood Geomorphology*, (ed.) V.R. Baker , R.C. Kochel and P.C. Patton , J.Wiley, 301-315.
13. Gupta A. 1995. Magnitude, frequency, and special factors affecting channel form and processes in the seasonal tropics. [in:] *Natural and anthropogenic influences in fluvial geomorphology*. The Wolman Volume (eds.) J.E. Costa, A.J. Miller, K.W. Potter and P.R. Wilcock), *American Geophysical Union Geophysical Monograph* **89**, 125-136.

14. Kale V.S. 1998. Monsoon floods in India: a hydro-geomorphic perspective. [in:] *Flood studies in India,* (ed.) V.S. Kale, Geological Society of India, Bangalore, *Memoir* 41, 229-256.
15. Krishnan A., Raman P.K. and Vernekar A.D. 1959. Probable maximum twenty-four hour rainfall over India. [in:] *Proceedings of Symposium on Meteorological and Hydrological Aspects of floods and Droughts in India,* 196-202.
16. Raghavendra V.K. 1982. A case study of rain storm in the eastern mountainous catchment of Brahmaputra leading to highest ever recorded flood level at Dibrugarh. *Proceeding of Int. Symp. on Hydrological Aspects of Mountainous Watersheds,* Roorkee, 139-144.
17. Bruijnzeel L.A. and Bremmer C.N. 1989. Highland-lowland interaction in the Ganges-Brahmaputra river basin: a review of published literature. International Centre for Integrated Mountain Development. ICMOD Occasional Paper No. 11.Kathmandu, pp. 136.
18. Gansser A. 1964. *Geology of the Himalayas.* J. Wiley, New York, pp. 289.
19. Iwata S. 1987. Mode and rate of uplift of the central Nepal Himalaya. *Zeitschrift für Geomorphologie, Suppl.-Bd.* 63, 37-49.
20. Selby M. J. 1988. Landforms and denudation of the High Himalaya of Nepal: results of continental collision. *Zeitschrift für Geomorphologie, Suppl. Bd.* 69, 133-152.
21. Heim A. and Gansser A., 1939, Central Himalayan. Geological observation of the Swiss Expedition 1936. *Hem. Soc. Sci. Nat.* 73, 1, pp. 245.
22. Hack J.T. 1960. Interpretation of erosional topography in humid temperate regions. *Am. J. Sci.* 258A, 81-96.
23. Starkel L. 1989a. Valley floor evolution in the marginal areas of the Himalaya Mountains the Khasi-Jaintia Plateau. *Zeitschrift für Geomorph., Suppl.-Bd.* 76, 1-8.
24. Verstappen H. Th. 1955. Geomorphologische Notizen aus Indonesien. *Erdkunde* 2, 9, 134-144.
25. Starkel L. 1969. Climatic or tectonic adaptation of the relief of young mountains in the Quaternary. *Geographia Polonica* 17, 209-229.
26. Goswami D.C. 1985. Brahmaputra River, Assam, India: physiography, basin denudation, and channel aggradation. *Water Resour. Res.* 21, 959-978.
27. Pal S. K. and Bagchi K. 1974. Recurrence of floods in Brahmaputra and Kosi basins: a study in climatic geomorphology. *Geographical Review of India,* 37, 242-248.
28. Weischet W. 1969. Der tropisch-konvektive und der aussertropisch-advektive Typ des vertikalen Niederschlagsverteilung. *Erdkunde* 19, 1, 6-13
29. Hagen T. 1969. Report on the geological survey of Nepal. Preliminary reconnaissance. *Denkschriften der Schweizerische Naturforschungs Gesellschaft* 86, Heft 1, pp. 185.
30. Dhar O.N., Kulkarni A.K. and Mandal B.N. 1988. A review of recent hydrometeorological studies on India rainfall. *Hydrology Journal of IAH* 9, 1, 1-12.

31. Hewitt K. 1972. Mountain environment and geomorphic processes. *Mount. Geomorph. B.C. Geogr. Ser.* **14**, 17-34.

32. Rapp A. 1974. Slope erosion due to extreme rainfalls, with examples from tropical and arctic mountains. *Report of the Commission in Present-day Geomorphological Processes (IGU)*, Gottingen, 118-136.

33. Selby M. J. 1974. Dominant geomorphic events in landform evolution. *Bull. of Int. of Assoc. of Engin. Geol.* **9**, 85-89.

34. Baker V. R., Kochel R. C. and Patton P. C. (eds.). 1988. *Flood Geomorphology*. J. Wiley, pp. 503.

35. Ergenzinger P. 1988. Regional erosion: rates and scale problems in the Buonoamico Basin, Calabria. *Catena, Suppl.* **13**, 97-107.

36. Ives J. D. and Messerli B. 1989. The Himalayan Dillema, Reconciling Development and Conservation. UN Univ. and Rontledge, London, pp. 272.

37. Fort M. 1997. Developpement et aleas naturels en Himalaya du Nepal: la crue de juillet 1993, bassin-versant de la Bagmati. *Geomorphologie, Relief, Processes, Environment*, **1**, 43-58.

38. Temple P. H. and Rapp A. 1972. Landslides in the Mgeta area, Western Uluguru Mts, *Tanzania. Geogr. Annaler* **54A**, 157-193.

39. Starkel L. 1978. First stages of the transformation of relief of the young uplifting mountains. *Studia Geomorph. Carp. Balc.* **12**.

39A. Unusual storm events and their Relevance to Dam Safety and Snow Hydrology. 1993. Central Board of Irrigation and Power, Publ. No. 234, New Delhi.

40. Vij G. K. and Shenoy R.C. 1968. Hydrology of Indian rivers. [in:] *Mountains and Rivers of India*, IGU Congress, Calcutta, 258-283.

41. Starkel L. 1996. Present-day formation of the southern part of Meghalaya Plateau. *Hill Geographer*, **Vol. 12**, No. 1, 2, 13-19.

42. Gohain K. and Parkash B. 1990. Morphology of Kosi megafan. [in:] *Alluvial fans*, (eds.) A. Rachocki, M. Church, J. Wiley, 151-178.

43. Basu S. R. and Sarkar S. 1990. Development of alluvial fans in the foothills of the Darjeeling Himalayas and their geomorphological and pedological characteristics in alluvial fans: A field approach (eds.) A.H. Rachocki and M. Church, J. Wiley, 321-333.

43A. Hooker J.D. 1854. *Himalayan Journals*. London, John Murray.

43B. Bose P.N. 1889-1890. The Darjeeling coal between the Lisu and the Ramthi Rivers. Records of the Geology.

43C. Garwood E.J. 1903. The Geological structure and physical features of Sikkim in around Kanchenjunga. (ed.) D.W. Freshfield, London.

43D. Suess E. 1885-1909. Das Antliz der Erde. Freytag.

43E. Ray S. 1947. Zonal metamorphism in the E. Himalaya and some aspects of local geology. *Q.J. Geol. Min. Metal Soc. Ind.*, **19(4)**.

43F. Ghosh A.M.N. 1950. Observation of the landslides of the 11th and 12th June, 1950; in the Darjeeling Himalayas. GSI Report, unpub.

43G. Auden J.B. 1956. Preliminary Geol. Report on dam sites on Tista River near Coronation Bridge. G.S.I.,

44. Griesbach G.L. 1899-1900. General Report, GSI.

44A. Hayden H.H. 1912. General Report for 1911 and 1912. *Rec. Geol. Survey of India,* Vol. 42 and 43, part 1 and 2, pp.70.

45. Middlemiss C.S. 1916. General Report for 1914. *Rec. Geol. Surv. India,* Vol. **45**, 2, pp.119.

46. Nautiyal S.P. 1966. On the stability of certain hillsides in and around Darjeeling, W.B. *Bull. of the Geol. Survey of India, Series B,* **15**, 1, 31-48.

47. Nautiyal S.P. 1966. On the stability of hill slopes in Jalapahar and Lebong Cantonment Areas, Darjeeling West Bengal. *Bulletins of* G.S.I., *Series* B, **15**, 1, 49-60.

48. Dutta K.K. 1966. Landslips in Darjeeling and neighbouring hill-slopes in June 1950. *Bull. of the Geol. Survey of India, Series B,* **15**, 7-30.

49. Dutt G.N. 1966. Landslides and soil erosion in the Kalimpong Subdivision, Darjeeling District and their bearing on the North Bengal Flood. *Bull. of the Geol. Survey of India,* Series B, 15, 1, 62-69.

50. Jain M.S. 1966. Geological Reconnaissance of the Lish and the Ramthi Valleys Kalimpong Sub-Division, Darjeeling District. *Bull. of the Geol. Survey of India, Series B,* **15**, 1, 80-88.

51. Hazra P.C. 1966. Geological note on the stability of hill slopes near N.B. M.R. and some buildings in Lebong Cantonment, Darjeeling, West Bengal. *Bulletins of the* G.S.I., Series B, No. 15, Part I, 1-6.

52. Starkel L. 1970. Cause and effects of a heavy rainfall in Darjeeling and in the Sikkim Himalayas. *Journal of Bombay Nat. Hist. Soc.* **97**, 1, 45-50.

53. Biswas B. and Bhadram G.V. 1984. A study of major rainstorms of the Teesta basin. *Mausam* **35**, 2, 187-190.

54. Agarwal A. and Narain S. (eds.). 1989. Floods, floodplains and environmental myths, State of Indian Environment. A *Citizen's Report* Vol. 3, Centre for Science and Environment, New Delhi, pp. 167.

55. Sinha B.N., Verma R.S. and Paul D.K. 1975. Landslides in Darjeeling district, W.B. and adjacent areas. *Bull.* G.S.I., *Series* B. No. **36**.

56. Basu S.R. and Sarkar S. 1985. Some considerations on recent landslides at Tindharia and their control. *Indian Journal of Power and River Valley Development,* Vol. **XXXV**, Nos. 10 & 11, 188-194.

57. Basu S.R. and Sarkar S. 1987. Eco-system *vis-a-vis* landslides - a case study in Darjeeling Himalayas. *Proceedings of the national Conference on Impact of Development on Environment,* Geographical Society of India, Calcutta, Vol. **II**, 45-50.

58. Basu S.R. and Ghatowar L. 1984. The Lish-Gish Basin – A study of its water resources. *Indian Journal of Power and River Valley Development,* Vol. **XXXIII**, No. **2**, 50-54.

59. Basu S.R. and Ghatowar L. 1986. A quantitative analysis of the long profiles of the Lish and Gish rivers of the Darjeeling Himalayas. *Indian Journal of Landscape System and Ecological Studies*, Vol. 9, No. 11, 66-70.
60. Basu S.R. and Ghatowar L. 1986. Long profiles of the lower courses of the Lish and Gish rivers. *Geog. Review of India*, Vol. **48**, No. 3, pp. 83.
61. Basu S.R. and Ghatowar L. 1988. Landslides and soil-erosion in the Gish drainage basin of the Darjeeling Himalaya and their bearing on North Bengal Floods. *Studia Geomorph. Carpatho-Balc.* **22**, 105-122.
62. Basu S.R. and Ghatowar L. 1988. Mining and Environment. A case study in the Lish basin of Eastern Himalayas. Mining and Environment in India, (Ed.), Himalayan Research Group, Nainital, 316-325.
63. Basu S.R. and Ghatowar L. 1990. The impact of landslides of fluvial processes in the Lish Basin of the Darjeeling Himalayas. *Geographia Polonica* **59**, 77-87.
64. Froehlich W., Starkel L. and Kasza I. 1991. Ambootia landslides valley in the Darjeeling Himalaya, active since 1968. *Bulletin of the Polish Acad. Sc., Series: Earth Sciences* **39**, 2.
65. Froehlich W., Starkel L. and Kasza Z. 1992. Ambootia landslide valley in Darjeeling Hills, Sikkim Himalaya, active since 1968. *Journal of Himalayan Geology* **3**, **1**, 79-90.
66. Froehlich W. and Starkel L. 1987. Normal and extreme monsoon rains – their role in the shaping of the Darjeeling Himalaya. *Studia Geomorph. Carpatho- Balc.* **21**, 129-160.
67. Sarkar S. 1991. Environmental degradation in the Upper Mahananda Basin - a case study of soil erosion and strategies for soil conservation. [in:] *Environmental Degradation and Developmental Strategies in India* **9**, 78-98.
68. Sarkar S. 1997. Some consideration on the fluvial dynamics of the river Mahananda, Siliguri. *Geographical Review of India* **59**, 11-24.
69. Sarkar S. 1998. Landslides in Darjeeling Himalayas, India. *Transactions of Japanese Geomorphological Union*, 5-20.
70. Pawde M.B. and Saha S.S. 1982. Geology of the Darjeeling Himalaya. Section 1B, G.S.I., Misc. Publications **41**(11), 50-54.
71. Nakata T. 1972. Geomorphic history and crustal movements of the Foot-hills of the Himalayas. The Sc. Reports of the Tohoku University, VII Series, *Geography*, **22**, **1**, Sendai, 39-177.
72. Bluszcz A., Starkel L. and Kalicki T. 1997. Grain size composition and age of alluvial sediments in the Tista valley floor near Kalijhora, Sikkim Himalaya. *Studia Geomorph. Carpatho-Balc.* **31**, 159-174.
73. Mallet F.R. 1874. On the geology and mineral resources of the Darjeeling District and the Western Duars. Memoir, G.S.I., **11**(1); pp. 72.
74. Kar N.R. 1962. Investigations on a piedmont drift deposit in the foot-hills of the eastern Himalayas and its glacial and periglacial significance. *Biuletyn Peryglacjalny*, **2**, 215-216.

75. Sarkar S. 1988. Rain-erosivity in the Darjeeling Himalaya region of W. Bengal. *Landscape system and Ecological Studies*, Vol. 12, No. 1.

76. Sarkar S. 1989. A geoenvironmental appraisal of the upper Mahananda basin of the Darjeeling Himalaya, West Bengal. Ph. D. Thesis, Department of Geography and Applied Geography North Bengal University, West Bengal, India, manuscript, pp.252.

77. Sharma J.L. 1993. Eco development plan for Ambootia Tea Estate, Kurseong (West Bengal) 1996-2000. IFS. Ambootia T.E., manuscript, pp. 221.

78. Nakata T. 1982. Active faults along the foot-hills of the Darjeeling Himalayas. [in:] The region: its cultural and physical aspects, Fukutake, Tokyo, 448-463.

79. Starkel L. 1977. *Paleogeografia holocenu.* (in Polish), PWN, Warszawa.

80. Müller M.J. 1980. Handbuch ausgewählter Klimastationen der Erde. Forschungstelle Bodenerosion der Univ. Trier, Mertesdorf (Ruwertal), 5.

81. Champion H.G. 1936. A preliminary survey of the forest types of India and Burma. *Ind. For Rcc.* (New Series), Vol. 1(1).

82. Troll C. 1939. A preliminary survey of the forest types of India and Burma. Ind. For. Rec. (New Series), Vol. I (1).

83. Schweifurth U. 1968. Vegetation of the Himalayas. [in:] *Mountains and Rivers of India*, (ed.) National Committee for Geography, I.G.C., 128-136.

84. Pinn F. 1986. The road of destiny (Darjeeling Letters 1839). Oxford University Press.

85. Das V. and Chakraborty P.K. 1982. Maladies of mountain ecosystem in the Darjeeling Himalaya. *Geographical Review of India*, 42-45.

86. Mitra S. 1975. The economy of the Gielle basin in the SubHimalayan Region of Darjeeling District. *Geog. Rev. India*, Vol. 37, No. 3, 320-324.

87. Lama S. 1994. Urban geomorphology of Darjeeling town. Unpublished Ph.D. thesis, University of North Bengal.

88. Bhattacharyya B. 1971. A genetic classification of settlement and their hierarchical order in the District of Darjeeling. *Geog. Rev. India*, Vol. 33, No. 3.

89. Banerjee B. 1982. Resource utilisation of Darjeeling Himalaya and conservation of ecology. *Geographical Rev India* 3, 1-15.

90. Vanzone G.S. 1989. Environmental problems of Darjeeling - Sikkim Himalaya. [in:] *The Eastern Himalaya, environment and economy*, (eds.) R.L. Sarkar and M.P. Lama, publ. Atma Ram, Delhi, 38-49.

91. Froehlich W., Gil E., Kasza Z., and Starkel L. 1989. Thresholds in the transformation of slopes and river channels in the Darjeeling Himalaya, India. *Studia Geomorph. Carpatho- Balc.* 23, 105-121, (reprinted in Mountain Research and Development 10,4, 1990, 301-312).

92. Chandra H. 1975. Landslides in Teesta valley. Proceedings of seminar on landslides and toe erosion problems with special reference to Himalayan Region, Gangtok, Sikkim, Indian Society of Engineering Geology, Calcutta, 147-164.

93. Dash A. J. 1947. Darjeeling: Bengal District Gazetters. Bengal. Gov. Press, Calcutta, 1-294.

94. Froehlich W. and Starkel L. 1995. The response of slope and channel systems to various types of extreme rainfall: A comparison between the temperate zone and humid tropics. *Geomorphology* **11**, 337-345.

95. Sanyal C.C. 1969. The flood of 1968. *Geographical Rev India* **31, 3,** 47-53.

96. Singh J., Rao S.M. and Dagra J.C. 1975. Selection and design of structures for protection and prevention of landslides and toe erosion. Proceedings of seminar on Landslides and toe erosion problems with special reference to Himalayan Region, Gangtok, Sikkim, Indian Society of Engineering Geology, Calcutta, 275-313.

97. Toy O.P. and Ramakrishnan P.S. 1981. Run-off and infiltration losses related to shifting agriculture (Jhum) in north-eastern India. *Environmental Conservation* **8**, 313-321.

98. Pandey A.N. and Pathak P.C. and Singh J.S. 1984. Water, sediment and nutrient movement in forested and non-forested catchments in Kumaun Himalaya. *Forest Ecology and Management* 7, 19-29.

99. Gilmour D.A., Bonell M. and Cassells D.S. 1987. The effects of forestation on soil hydraulic properties in the Middle Hills of Nepal: a preliminary assessment. *Mountain Research and Development* 7, 239-249.

100. Sharma K.D. and Correia J.F. 1987. An upland soil erosion model derived from the basic principles. *Earth Surface Processes and Landforms* **12**, 205-210.

101. Slupik J. 1973. Zróznicowanie splywu powierzchniowego na fliszowych stokach górskich. *Dokumentacja Geograficzna* IG PAN **2**, pp. 118.

102. Bruijnzeel L.A. 1991. Hydrological impacts of tropical forest conversion. *Nature & Resources* **27** (2), 36-46.

103. Sidle R.C., Pearce A.J. and O'Loughlin C.L. 1985. Hillslope stability and land use. *Agu Water Resources Monograph* **11**, pp. 140.

104. Patel S. and Soja R. 1995. Runoff and suspended sediment transport in the Peshok Jhora (Himalaya) catchment basin. *Proc. Geogr. Conf.*, Bruxelles.

105. Ray S. and Sen Sharma S.B. 1967. Geological report on the stability of hill slopes in and around Darjeeling town, Darjeeling district, W.B. GSI Report, unpub.

105A. Ninth Working Plan for the Darjeeling Forest Division. 1955. Northern Circle 1952-53 to 1961-62. 1, Govt. of West Bengal, Direct. of Forests.

106. Basu S.R., Sarkar S. and Lama S. 1998. Causes and consequences of landslides in the Darjeeling Town. *Journal of Vidyasagar University*, Vol. **II,** No 1, 1-10.

107. Dasgupta M. 1986. Forest management in Darjeeling Hill areas from British Raj to Swaraj. [in:] The Eastern Himalaya. Environment and Economy, New Delhi, 134-174.

108. Lama S. and Sarkar S. 1995. Geomorphology and urban activities a case study of Darjeeling Town. Himalayan Paryavaran, 4-12.

109. Rumba U. 1986. Problems and prospect of water supply in Darjeeling town in the Eastern Himalayas: Environment and Economy, (ed.) Atma Ram and Sons, 67-73.

110. Bandyopadhyay M. 1980. Progress Report on slope stability study of Toongsoong area, Darjeeling Town. G.S.I. Report, unpub.

111. Basu S.R. 1998. Landslide along the arterial routes to Darjeeling and their control. Himalayan Natural Resources (ed.), 245-257.

112. Lahiri S., and Gangopadhyay P.K. 1974. Structural pattern of rocks in Pankhabari-Tindharia Region in Darjeeling District, W. B. *Himalayan Geology*, Vol. **IV**, Part I, 151-170.

113. Basu S.R. and Ghatowar L. 1988. Landslides in the Lish basin of the Eastern Himalayas and their control. Proceedings of the International Seminar on Geomorphology and Environmental Management, (Ed.) Allahabad University, 428-443.

114. Basu S.R. and Ghatowar L. 1988. Landslides in the Lish-Gish basins of the eastern Himalayas, West Bengal and their control. *Indian Journal of Landscape Systems and Ecological Studies*, Vol. **11**, No. 1, 77-88.

115. Basu S.R. and Ghosh L. 1993. A comprehensive study of landslides and floods in the Lish basin of the Darjeeling Himalaya. *Indian Journal of Power and River Valley Development*, Vol. **XLIII**, No. 10, 196-203.

116. Morisawa M. 1968. Streams, their dynamics and morphology. Mc. Graw Hill, 12, pp. 174.

117. Sawicki L. 1917. Osuwisko ziemne w Szymbarku i inne zsuwy powstale w Galicyi Zachodniej w r. 1913. *Rozpr. Wydz. Mat.-Przyr. A.U. 16*, Ser. III, Dzial A, 227-313.

118. Ergenzinger P. 1992. A conceptual geomorphological model for the development of a Mediterranean river basin under neotectonic stress (Buonamico basin, Calabria, Italy). [in:] Erosion, Debris Flows and Environment in Mountain Regions, (eds.) T.R. Davies and D.E. Walling, Proc. Chengdu Symp., July 1992, IAHS Publication No. 209, 51-60.

119. Sorriso-Valvo M. 1989. Studies on high-magnitude geomorphic processes in Southern Italy and Algeria. Studia Geomorphologica Carpatho-Balcanica **23**, 23-38.

120. Chattopodhyay A. 1986. A survey on the occurrence of landslides and their impact on the economy of Darjeeling District. [in:] *The Eastern Himalaya, Environment and Economy*, New Delhi, 74-87.

121. Hearn C. and Jones D.K.C. 1987. Geomorphology and mountain highway design: some lessons from the Dharan-Dhankuta Highway, East Nepal. [in:] *International Geomorphology*, Part I, (ed.) V. Gardiner, J. Wiley, 203-219.

122. Caine N. and Mool P.K. 1981. Channel geometry and flow estimates for two small mountain streams in the Middle Hills, Nepal. *Mountain Research and Development* **1,** 3-4, 231-243.

123. Froehlich W., Gil E., Kasza I. and Starkel L. 1990. Thresholds in the transformation of slopes and river channels in the Darjeeling Himalaya, India. *Mountain Research and Development*, Vol. **10** (4), 301-312.

124. Sen S. 1968. Major changes in river courses in recent history. [in:] Mountains and Rivers of India, (ed.) B. C. Law, *Nat. Com. for Geography*, Calcutta, 211-220 Series B. No.15, part 1, 7-30.
125. All India Soil and Land Use Survey Organisation. Ministry of Agriculture, Report AGRI-509, July 1980.
126. Ries J. 1994. Bodenerosion in der Hochgebirges des ostlichen Zentral-Himalaya untersucht am Beispiel Banti/Bhandar/Surma area, Nepal, *Freiburger Geographische Hefte* 42, 397.
127. Dey S. 1990. Design flood of the river Teesta in North Bengal. *Indian Journal of Earth Science* 17, 3-4, 172-179.
128. Starkel L., Froehlich W. and Soja R. 1998. Floods in Sikkim Himalaya - their causes, course and effects. *Memoir Geol. Soc. of India* **41**, 101-118.
129. Lahiri S. 1981. Statistical forecasting of heavy rain and floods in the river Teesta. *Mausam* **32**, 1, 41-44.
130. Rai R.N., Singh K.A. and Solanki R.C. 1988. A case study of water flows of some hill springs of Sikkim. *Indian Journal of Soil Conservation* **16**, 1, 52-56.
131. Sanyal C. C. 1967. The river Tista. *Geographical Review of India* **29**, 4, 13-28.
132. Peart M. R. and Walling D.E. 1986. Fingerprinting sediment source: The example of a drainage basin in Devon, UK. [in:] Drainage Basin Sediment Delivery, (ed.) R.F. Hadley, Proc. Albuquerque Symp., August 1986, IAHS Publ. No. 159, 41-55.
133. Froehlich W. and Walling D.E. 1992. The use of fallout radionuclides in investigations of erosion and sediment delivery in the Polish Flysch Carpathians. [in:] Erosion, Debris Flows and Environment in Mountain Regions, (eds.) T.R. Davies and D.E. Walling, Proc. Chengdu Symp., July 1992, IAHS Publ. No. 209, 61-76.
134. Gerrard J. 1994. The landslide hazard in the Himalayas; geological control and human action. [in:] Geomorphology and natural hazards, (ed.) M. Morisawa, Proceedings of the 25th Binghamton Symposium in Geomorphology, September 24-25, 1994, Elsevier, 221-230.
135. Strakhov N.M. 1967. Principles of Lithogenesis. I, New York, pp. 245.
136. Walling D.E. and Webb B.W. 1983. Patterns of sediment yield. [in:] *Background to Paleohydrology*, (ed.) K.J. Gregory, J. Willey, Chichester, UK, 69-100.
137. Subramanian V. 1979. Chemical and suspended sediment characteristics of rivers of India. *J. Hydrol.* 44, 37-55.
138. Subramanian V. 1996. The sediment load of Indian rivers - an update. *IAHS Publ.* **236**, 183-189.
139. Kothyari U.C. 1969. Erosion and sedimentation problems in India. *IAHS Publ.* **236**, 531-540.
140. Narayana V.V.D. 1987. Downstream impacts of soil conservation in the Himalayan region. *Mountain Research and Development* 7, 287-298.

141. Costa J.E. 1988. Rheologic, geomorphic and sedimentologic differentiation of waterfloods, hyperconcentrate flows and debris flows. [in:] *Flood Geomorphology*, (eds.) V.R. Baker, R.C. Kochel and P.C. Patton, J. Wiley, 113-122.

142. Brunsden D., Jones D.K.G., Martin R.P. and Doornkamp J.C. 1981. The geomorphological character of part of the Low Himalaya of Easter Nepal. *Zeitschrift für Geomorphol.*, (N.F.) 37, 25-72.

143. Costa J.E. and O'Connor J.E. 1995. Geomorphically effective floods. [in:] Natural and Anthropogenic Influences in Fluvial Geomorphology, (eds.) J. E. Costa, A. J. Miller, K. W. Potter and P. R. Wilcock, The Wolman Volume, AGU *Geophysical Monograph* 89, 45-56.

144. Mukhopadhyay S.C. 1982. The Tista Basin. Calcutta, New Delhi, pp. 308.

145. Abbas N. and Subramanian V. 1984. Erosion and sediment transport in the Ganges river basin (India). *Journal of Hydrology* 69, 173-188.

146. Froehlich W. and Walling D.E. 1998. Zastosowanie Cs^{137}, Ra^{226} i Pb^{210} do oceny natezenia wspólczesnej sedymentacji na równinach zalewowych Niziny Gangesu i Bramaputry. VI Konferencja "Metody chronologii bezwzglednej", Streszczenia, Gliwice-Rudy, 24-27 marca 1998. Laboratorium ^{14}C - Zaklad Zastosowan Radioizotopów, Instytut Fizyki, Politechnika Slaska.

147. Bewen K.J. 1981. The effect of ordering on the geomorphological effectiveness of hydrological events. *Inter. Assoc. Sci. Hydr. Publ.*, 132, 510-526.

148. Froehlich W. and Starkel L. 1993. The effects of deforestation on slope and channel evolution in the tectonically active Darjeeling Himalaya. *Earth Surface Processes and Landforms* 18, 285-290.

149. Brunsden D. 1993. Barriers to geomorphological change. [in:] *Landscape Sensitivity*, (eds.) D.S.G. Thomas and RJ. Allison, J. Wiley and Sons, Inc. Chichester, 7-12.

150. Shiklomanov I.A. 1990. Climate and water resources. *Hydrological Sciences Journal* 34, 5, 495-529.

151. Starkel L. 1993. Late Quaternary continental palaeohydrology as related to future environmental change. *Global and Planetary Change* 7, 95-108.

152. Hamilton L.S. 1987. What are the impacts of Himalayan deforestation on the Ganges-Brahmaputra lowlands and delta? Assumptions and facts. *Mountain Research and Development* 7, 256-263.

153. Starkel L. 1989. Global paleohydrology. *Quaternary Internationals* 2, 25–33.

154. Landsberg H.E. (ed.), 1977. The climate of the Indian Subcontinent. [in:] *World Survey of Climatology*.

155. *Indian Journal of Meteorology and Geophysics*. 1969.

156. *Census Reports*. 1991. Darjeeling, Darjeeling Municipality. unpub.

157. Plan for Darjeeling Hill Areas 1980-85.

158. Discharges of selected rivers of the world. 1971. Vols. II, III, Paris, UNESCO.